Faculty of Engineering of the University of Porto

Study on the contribution of thermal mass indoors placed on windowsills and jambs

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Abstract

Thermal inertia is an important property of some materials in buildings that helps to moderate thermal amplitude and the rate of variation of indoor temperatures. By decreasing the time occupants might be exposed to conditions of too high or too low temperatures, it gives an important contribution to providing thermal comfort conditions, and thus contributes towards a more sustainable building energy performance through the use of non-polluting passive solutions.

The usefulness of thermal inertia is particularly relevant in countries with temperate climates, such as Portugal and other Mediterranean Basin countries, where passive solar strategies and designs have the highest potential to contribute towards passive comfort. This is found in many vernacular architecture examples all over these countries, which tend to use massive wall constructions with very high thermal inertia to keep spaces cool in summer and store solar heat gains in winter.

While the use of massive materials in walls would be the best option to providing a space with high thermal inertia, by leaving indoor surfaces in contact with the indoor air while thermally insulating the outdoor surfaces, there are a number of situations where this might not be simple, permitted or even possible to implement. In such cases, it is here hypothesized that higher thermal inertia can be achieved through the placement of massive and dense materials (e.g. granite, slate, brick or marble) on the surfaces around windows, or in other words, in the windowsill and jambs. The use of high thermal inertia materials can render the indoor environments generally more comfortable, but during the summer these elements have to be shaded to not risking making the indoor conditions even worse.

In this work, the potential of this sort of solutions was investigated through a number of simulations carried out using the popular building energy dynamic simulation software package Energyplus^{TM}.

The models were set to study the impacts of high thermal inertia materials against a more traditional solution (wood), while in winter and summer periods, and for different window orientations.

The results show that slate is the studied material with the best performance in regard to indoor comfort. Furthermore, the investigated surface around the window showing the greatest potential depends on the window's orientation. When facing south, the windowsills are the elements with the largest contribution to the thermal comfort of the building, while when facing Southwest it is the east jamb.

Resumo

A inércia térmica é uma importante propriedade de certos materiais usados em edifícios que permite moderar a amplitude térmica e a taxa de variação da temperatura em espaços interiores. A redução do tempo de exposição dos ocupantes a temperaturas demasiado elevadas ou reduzidas melhora as condições de conforto térmico, assim contribuindo para um desempenho do edifício mais energeticamente suficiente através do uso de soluções passivas não poluentes.

A utilidade da inércia térmica é particularmente relevante em países com climas temperados, como por exemplo Portugal e outros países da bacia mediterrânica, onde é sabido que as soluções solares passivas têm um elevado potencial de contribuírem para o conforto passivo. Este facto é encontrado em diferentes exemplos na arquitetura vernacular destes países, que tendem a usar construções de paredes maciças com uma elevada inércia a fim de manter os espaços frescos no Verão e armazenar ganhos solares durante o Inverno.

O uso de materiais maciços nas paredes seria a melhor opção para se conseguir um espaço com elevada inércia térmica, deixando as superfícies exteriores em contacto com o ar interior através do próprio isolamento das superfícies pelo exterior. No entanto há um conjunto de situações nas quais isto não é simples, ou sequer permitido ou até possível de implementar. Para estes casos, coloca-se aqui a hipótese de que o aumento da inércia térmica possa ser conseguido através da colocação de materiais maciços e densos (por exemplo: granito, lousa, tijolo e mármore) em superfícies à volta das janelas, ou seja, no peitoril e nas ombreiras. O uso de materiais de elevada inércia térmica visa tornar os espaços interiores geralmente mais confortáveis, mas no Verão estes elementos necessitam de ser sombreados, de forma a manter as condições de conforto no interior de edifício.

Nesta tese, o potencial deste tipo de soluções foi investigado através de um número de simulações realizadas com um software de simulação dinâmica de energia, o Energyplus^{TM}.

Os modelos permitiram o estudo do impacto da elevada inércia térmica dos materiais, em alternativa à solução mais comummente utilizada, a madeira, durante um período no Inverno e no Verão e para diferentes orientações da janela.

Os resultados demonstram que a lousa é o material estudado com o melhor comportamento relativamente ao conforto do espaço interior. Além disto, das superfícies consideradas à volta da janela a que mostra ter o maior potencial depende da orientação da janela. Quando a janela é virada a sul, o peitoril é o elemento com a maior contribuição para o conforto térmico do edifício, enquanto que quando a janela está orientada a sudoeste, a maior contribuição para o conforto é a da ombreira orientada a este.

Acknowledgments

Fundamental individuals contributed to the completion of this dissertation, thus my first acknowledgement goes to them.

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1 Introduction

The concept of sustainable development was first introduced in 1980's by The World Conservation Strategy, following the emergence of global environmental issues, namely climate change and the ozone depletion. Sustainability was later defined on the Brundtland report [UNWC, 1987], as the "development that meets the needs of the present without comprising the ability of future generations to meet their own needs", a definition that is still often cited to this day [Vos, 2007].

In developed countries, the energy demand of buildings generally represents approximately one third of all the primary energy used [Vorstaz, et al., 2014]. Part of the energy needs are for ambient heating or cooling and they tend to have a significant expression, particularly in places with extreme climates, but are still quite relevant even in temperate climates. The European Commission has detailed multiple venues to address the energy performance of buildings, such as the Energy Performance of Buildings Directive (EPBD) [EPBD, 2010], or even the Energy Efficiency Directive [Energy efficiency directive, 2012]. Moreover, the Commission has more recently published a communication restating the high importance and relevance of addressing the specific energy demand for heating and cooling purposes [European Comission, 2016].

With the Paris Agreement, European countries have committed to achieving a reduction of 40% in greenhouse gas emissions until 2030 [European Commission, 2015]. That means that all sectors, including buildings, must go through a substantial number of improvements, starting by the way buildings are designed and built, in order to explore the potentialities of the local climate and thus maximize their contribution towards a more sustainable use of material, financial and energy resources. From this perspective, passive solar solutions and designs gain a particular relevance and emerge as a feasible and increasingly researched option in the path towards the reduction of the demands for heating and cooling in buildings [IEA, 2013].

The reduction of a building's thermal energy needs can be achieved in various ways, namely: starting by maximizing the potentialities of the building's location, optimizing its orientation, controlling excessive solar gains through proper shading solutions (while still allowing beneficial solar heat gains), using high quality windows, being careful with the rooms' interior setup, installing adequate levels of thermal insulation (while respecting the proper levels of accessible indoor thermal mass), using natural ventilation, nocturnal ventilation in the summer, among many others [Oliveira Fernandes, 2000].

Due to the specific local conditions and climate, as well as the lack of more advanced modern technologies, past populations naturally looked for solutions that would improve indoor comfort conditions. Over many millennia of knowledge development, observation, education and even trial and error, each location saw the emergence of its locally adapted vernacular architectural and design solutions, mostly exploring solar passive performance. For instance, even in a small country such as Portugal the differences are quite clear between the typical architecture of buildings in the warmer south, with small windows, white walls, and thick rammed-earth walls, and the architecture in colder north, relying on largely glazed verandas for solar heat capture. Given its origins, vernacular architecture naturally explores low energy solutions, using local materials, and follows a design model closely linked to the outside natural environment.

The energy required to provide comfort conditions in a house depends not only on the energy efficiency of the heating or cooling devices, but primarily and to the greatest extent, on whether the architectural design properly considers the local microclimate characteristics and local solar potential to decrease energy needs for thermal conditioning of the indoor environment. The latter, that has recently been called energy sufficiency, means that each country, each city and each building is faced with a different set of conditions requiring wisely adapted architecture standards and designs.

When these differences are ignored, the results tend to show problems in practice. “Energy efficient buildings in Mediterranean areas are usually facing problems resulting from the use of Northern Europe examples, which do not face summer climate problems”, since a successful solution found for a region is adopted in a given country with distinct climate conditions [Sayligh, 2014]. The recent trends for ‘international architecture’, facilitated by globalization, communication and knowledge transfer, have been responsible for many buildings performing badly, which typically ends up requiring fixes that rely on energy-consuming equipment that could otherwise have been avoided.

This dissertation addresses the potential of increasing thermal inertia in buildings through the specific use and placement of massive elements on indoor surfaces next to windows, namely windowsills and jambs, which are subjected to the impact of direct solar radiation.

While the work presented in this thesis is expected to be applicable to any building, it bears in mind, particularly, the case of rehabilitation, and is thus more relevant in conditions where the freedom for design and construction is restricted, by relevant reasons such as the cultural-historic ones. This is the case, for instance, of the rehabilitation of historic buildings in downtown Porto, where buildings made in granite stone are subjected to cultural limitations, particularly in regard to the exterior main façades, which cannot suffer interventions. This generally means thermal insulation ends up being installed on the inner surfaces of walls, thus voiding the potential thermal inertia effect of the stone walls [Oliveira Fernandes, 2010].

By exploring the option to intervene on the surfaces around the windows, it is expected that not only can an increase in thermal inertia be achieved, but also that these may end up acting as better embedded solar collectors, storing the impinging solar radiation throughout the day, and releasing it overnight.

This thesis thus aims to answer the following questions:

1. Are the windowsill and jambs interesting technical options for increasing a space's thermal inertia through the use of heavier materials?
2. Is there any benefit from these elements receiving direct solar radiation?
3. From a selection of some common massive materials, which ones might perform better and what is the impact of the materials' optical properties?

1.1 Dissertation's structure

This dissertation is divided in 8 chapters. The overall theme of the thesis is introduced and presented in this first chapter. The 2nd chapter "State of the art" explains some of the topics this dissertation is built around, such as the rehabilitation of buildings and thermal inertia. The different parameters of the simulations are characterised in the 3rd chapter. In the 4th chapter the results of the simulations are outlined. The discussion of these results is done in the 5th chapter. The conclusion of the obtained results is included in the sixth chapter. The last chapter explains some of the topics which could be explored in future works.

2 State of the art

Given the particular relevance of this thesis's findings to the rehabilitation of existing buildings, namely the ones where there might be particular technical or regulatory constraints to the installation of thermal insulation from the outside, this chapter starts by addressing this topic.

The use of passive solutions are later briefly explained, while thermal storage and thermal inertia are further described. Thermal comfort is also explored, and its analysis is included in the "Results" chapter.

2.1 Rehabilitation

Old buildings can be chronologically defined as buildings which were constructed in the period prior to the Second World War, before the application of concrete in structures became common practice. This specific group of buildings includes listed and heritage buildings predominantly constructed with stone, wood, lime or glass.

The structure of buildings located within a city suffer from degradation throughout time, which is caused by factors such as: the natural aging process, the buildings' usage by people, and the lack of organization regarding land use planning [Portal da habitação, 2017].

Rehabilitation regarding buildings can be defined as the intervention necessary to render a given building comfortable, functional, and safe, even for the same purpose, without compromising its typology, architecture, or constructive system.

Although the number of rehabilitated buildings in Portugal represents only 6.2% of the total of constructions, the number of buildings which need intervention is much higher: 34% of all constructed buildings [CPCI, 2010].

Given its long history, the case in the city of Porto is more demanding than the national average, as, on the one hand, there are two thirds of the buildings in need of rehabilitation and, on the other hand, the level of requirements regarding the cultural and the new social context. This is most significant in Porto's historic centre, encompassing 6% of the city's buildings, in the oldest and most densely populated area of the city [Oliveira Fernandes, 2010]. The rehabilitation of these buildings has taken on a prominent role in the reconstruction of this part of the city, but it frequently faces constraints, namely in the intervention of the façades which cannot be changed. A recent study conducted by a consulting company shows that private investors spent more than 1.100 million euros between 2005 and 2015 in Porto's rehabilitation projects [Dinheiro Vivo, 2017].

People's habits trigger a rise in energy consumption, namely for comfort, and thus the envelope of the building should not necessarily be one of the factors contributing towards increased energy demand but rather a contributor to energy efficiency [Oliveira Fernandes, 2010]. Since rehabilitated buildings do not have the needed insulation to maintain thermal comfort conditions in the different rooms of the building, the use of environmental- and economically sustainable systems, such as passive solutions, instead of using heat originated from polluting sources, can be the solution.

One successful example of the implementation of solar passive design and principles can be found in one social housing building in Vila do Conde (1996). The fact that the block of flats is well insulated, with multiple windows facing South receiving direct solar radiation, while also adequately shaded, enables an almost absent need for energy used on heating. Figure 1 shows that most of the energy is used in the heating of water and on kitchen equipment [Oliveira Fernandes, 2000], with 21% of the total being provided in the way of solar thermal energy and the remaining roughly split half and half in natural gas and electricity. Remarkably enough is the fact that almost no energy use for space heating was observed during the monitoring year.

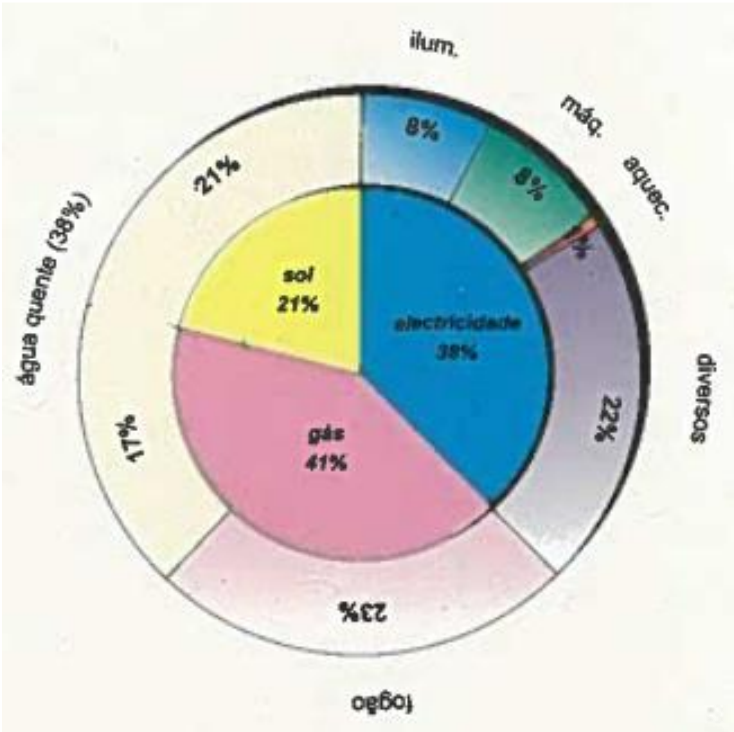

Figure 1. Disaggregation of final energy by use and energy vector in one flat at a social housing building of Vila do Conde [Oliveira Fernandes, 2000]

2.2 Passive solar solutions

Passive solar solutions primarily aim to contribute to a better thermal performance through the utilisation of solar gains. Among many other aspects, the solar passive performance of a building is naturally influenced by the use and location of the thermal mass in the building as well as by the windows' characteristics and their interaction with other building elements close by.

The thermal mass facilitates the storage and subsequent energy replenishment in the interior of the building. This process is influenced by the climate where the building is located, namely by the temperature of the exterior environment and by the incident solar radiation in the envelope of the building [Ferreira Duarte, 2013]. The thermal mass acts as heat storage volume in a dynamic process of delayed near-equilibrium with the indoor air temperature. This enables it to capture heat when the temperatures are increasing, and release it at a later time, when air temperature lowers. The materials can further absorb thermal energy impinging in the form of direct solar radiation converting it into heat, which is then stored in its mass.

When the mass is exposed to the sun, the effects of radiation are delayed by the direct storage that can decrease indoor temperature's thermal variations. There are materials that have higher storage capacity, thus allowing a lower fluctuation in temperature in the building's interior.

The thermal storage coefficient (TSC) assesses the capacity of the materials to store the excess heat gained from outdoors or generated indoors. This coefficient is defined by the ratio of the difference between the maximum (q_{max}) and minimum flux (q_{min}) of heat when the infinite thickness (t) materials are heated during a fluctuations' period.

$$TSC = \frac{q_{max} - q_{min}}{t_{max} - t_{min}}$$

If the materials possess constant thermal properties, the coefficient depends solely on the conductivity, specific mass (in *kg/m*^{3}) and specific heat of the material. New materials have recently emerged, namely phase changing materials (PCM) discussed below, which due to their nature, store a part of the heat in a latent form. The method to obtain the storage coefficient for these type of materials is not possible to simplify [Ling, et al.,2016].

Besides being assessed by the thermal storage coefficient, the main thermal properties related to heat storage are: thermal conductivity, specific heat capacity, specific mass and thermal diffusivity.

Thermal diffusivity (α_t) is defined by the other 3 mentioned variables, and is obtained dividing thermal conductivity (k) by the volumetric heat capacity.

$$\alpha_t = \frac{k}{\rho c}$$

Specific mass (ρ) and specific heat (c) are two properties which are normally used in a thermodynamic analysis. The multiplication of these two variables defines the volumetric heat capacity and measures the ability of a material to store thermal energy. Thermal diffusivity measures the ability of a material to conduct heat relative to its ability to store heat. “Materials of a large α_t will respond quickly to changes in their thermal environment, while materials of small α_t will respond sluggishly, taking longer to reach a new equilibrium condition” [Incropera,et al,2007].

If a material has a high thermal diffusivity, it can rapidly conduct heat and thus, in the case of a wall, its temperature will be similar to the room temperature [Gagliano, et al., 2014]. However, when it comes to concrete, the thermal conductivity does not affect the variation in temperature throughout the day, since the thicknesses studied (0.1-0.3 m) of concrete are sufficient to lower the amplitude of variations that might happen [Karlsson, et al., 2013].

High volumetric heat capacity leads to high thermal inertia, which indicates that the energy stored in the building’s structure mass during the day from solar and internal gains may be later released into the interior space during the night time when necessary.

2.3 Thermal Inertia

Thermal inertia in buildings helps to counteract temperature variations in its interior. It is associated with the capacity of the building to store heat in its constructive elements, and it is linked to buildings with massive walls [Stephanie,2013]. Buildings with higher thermal inertia tend to provide more stable indoor temperatures, which means the rate at which the indoor temperatures decrease and increase is slower.

Thermal mass has a more significant effect in locations where the outdoor air temperature amplitude is higher [Sadineni, et al., 2011]. The positive effects of thermal inertia are more closely felt in climates where the variation between the diurnal temperature is above 10°C. This can be explained by the fact that the heavier mass of the building helps to reduce the effect of the outside variation of the temperature in the interior conditions [Gagliano, et al., 2014]. "In the past, wall constructions of heavy materials were considered the major passive method to control indoor ambience performance; however, recent studies have shown that other parameters like solar gain and rate of air change influence this indoor ambience" [Orosa, et al., 2012]. For example, ventilation through the opening of a window has a positive result on the increase of the convection heat transfer coefficient which eases the release of heat by massive walls during the night period, mostly in summer.

Even though the synergic effect of high thermal mass with nocturnal ventilation allows for spaces to remain comfortable when solar gains are minimized over the day, there are still some situations when it might not be possible to cool down the buildings exclusively through natural ventilation in a Mediterranean climate. This is the case, for instance, when thermal amplitude is too small and outdoor air temperatures do not cool enough over the night time.

2.3.1 Windows and thermal inertia

A window is composed of one frame and one or more glass leaves, and its aim is to provide light to the interior spaces and views of the exterior surroundings, while protecting from noise, thermally isolating, and controlling natural ventilation.

The role of fenestration is essential in order to provide illumination and visual comfort in a given building. In addition, windows allow the ventilation of the space and the entry of solar radiation when it is advantageous. Apart from fenestration, the surfaces around the window also have a relevant role in terms of thermal comfort and in what comes to providing extra thermal mass. Window frames should also minimize the effect of thermal bridges and losses through infiltration. Windows' edges have a higher impact on windows with smaller area [Sadineni, et al., 2011].

During winter, in places with windows facing south and heating sources inside the building in order to hinder losses to the exterior, placing elements with higher mass into contact with heated interior air enables a better storage of heating energy.

2.3.2 New materials and their relation to buildings with high thermal inertia

Many recent studies on thermal inertia have explored the potential of phase changing materials (PCM). These absorb a high quantity of heat in association with the partial fusion of the material. This fusion (phase change) requires a supplemental amount of heat to turn the molecules from solid to liquid state, thus acting as an additional apparent mass, storing that extra heat. This heat is called latent heat, as it does not entail a change of temperature in the material. Given the reversibility of this process, when the temperature falls below PCM's fusion temperature, typically during the night, the materials release the previously stored heat and become solid again [Hichem, et al., 2013].

PCM are frequently incorporated into bricks or mortars which are used in the construction of buildings' façades. The parameters which affect thermal inertia in regard to this material are: the type of PCM, the method used in placing them in bricks, and the quantity of PCM that must be used. The change in the brick's geometry will allow for the required quantity of PCM to be minimized, and will enable the improvement of the brick's thermal inertia [Hichem, et al., 2013].

It has also been shown that phase changing materials are possible to incorporate into furniture. The furniture has a significant impact on the indoor space's humidity and on the thermal comfort, because of its high surface area which can reach up to 50% of all the available surface area in a given room [Johra, et al., 2017].

Other than phase changing materials, some studies have also reported on the emergence and development of materials that contribute to a high thermal inertia, such as ultra-lightweight concrete. Ultra-lightweight concrete is a material composed of recycled glass or micro silica and a combination of concrete. Constructions with ULWC (ultra-lightweight concrete) can be compared to constructions with heavy materials, that is to say high thermal inertia, for long periods of time, and to constructions with lightweight materials for shorter periods of time. Constructions with this type of concrete introduce a new concept entitled "monolithic walls", which are walls composed of one massive block [Roberz, et al., 2017].

2.4 Thermal comfort

The ultimate reason for considering thermal inertia and indoor air temperatures, is to provide comfortable conditions to a space's occupants with the minimum amount of extra heating or cooling energy from climatization devices. In this sense, thermal comfort describes an individual's state in regard to how he/she feels when standing in a given environment: whether hot or cold. In fact, ASHRAE defined thermal comfort in 1966 as “that condition of mind which expresses satisfaction with the thermal environment”. While this definition is scientifically accepted, it is still discussed to this day [Parsons, 2010]. In addition to air temperature, multiple other factors influence the perception of thermal comfort indoors, such as air relative humidity, air velocity at skin level, radiative temperature of the surrounding objects, activity and metabolic rate [Wang, et al., 2015]. For instance, when temperatures are high, the perception of comfort will be influenced by the perspiration and evaporation capability to dissipate heat away from a person’s body. However, when air relative humidity is close to 100%, that effect is very limited and, thus, the person will have a larger probability of feeling uncomfortable.

As stated in its description, thermal comfort is intrinsically linked to the psychological state of different individuals. Consequently, the scales created to establish the level of comfort are subjective [Parsons, 2010].

The creation of environments which have the capacity to provide thermal comfort can be accomplished by exploring the environmental variables discussed above. Some examples are: increasing air movement by opening windows which although may not lower the temperature, the breeze can be sufficient for people to feel comfortable; adjusting clothing levels according to each individual’s particular preferences, activity level and natural metabolic rate; through the reduction of the air temperature in a building with the help of an air conditioner during a heat wave [Parsons, 2010].

2.4.1 The adaptive thermal comfort

In the case of the adaptive method, thermal comfort is given by a range of temperatures that changes throughout the year, in response to people's natural expectancy, clothing levels and activity being linked to the record of local outdoor temperatures. Since outdoor temperatures change throughout the different seasons of the year, the thermal comfort temperature also alternates. Comfort norms are generally based on studies conducted in spaces that are not acclimated, hence relying on natural ventilation and in close dialogue with the outdoor environment.

According to the standardization methods, for this model to be applicable, the space should have a window opening to the exterior, using natural ventilation, and for spaces where occupants are near sedentary, i.e. with metabolic rates ranging from 1 met to 1.3 met [ASHRAE, 2008].

The linearization of the statistical analysis in the adaptive comfort model, is conveyed through the following equation and subsequent graphical representation (Figure 2).

$$Comfort\ temperature\ (°C) = 0.31(mean\ outdoor\ monthly\ air\ temperature) + 17.8$$

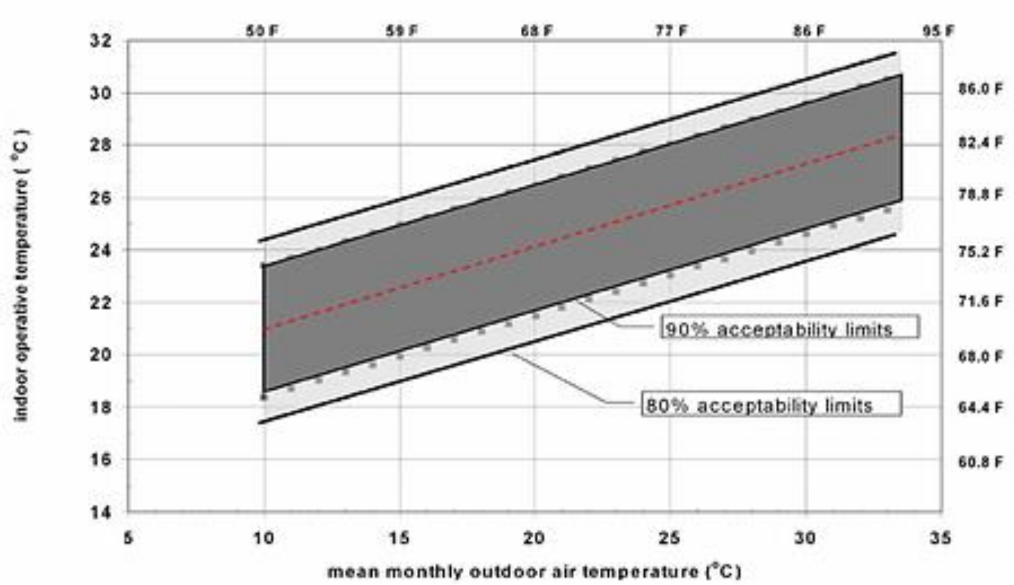

Figure 2.The adaptive comfort standard (ASHRAE) in naturally ventilated spaces [ASHRAE, 2008]

There are two thermal acceptability intervals, encompassing either 90% and 80% acceptability limits, meaning that the statistical analysis gives a probability of 90% or 80% of people feeling comfortable in that range of temperatures. These ranges were obtained through the “Group mean thermal sensation vote” (Fanger’s PMV) and “thermal dissatisfaction” (Fanger’s PPD).

The thermal amplitude acceptability interval for the 80% and 90% limits is respectively ± 3.5 ºC e ± 2.5 ºC. These acceptability limits have already taken into account people’s clothing level and the fact that it is an environment with natural ventilation. The standard further restricts its applicability to exterior temperatures ranging from 10 to 33.5°C [ASHRAE, 2008] as outside this range, the linearity of the statistical data was no longer visible. For this work, it was assumed that for temperatures below 10°C or above 33.5°C, the acceptability temperature range for 10°C or 33.5°C are applied (i.e. the comfort range of temperatures no longer develops towards lower or higher temperatures).

2.4.2 Discomfort degree-hours coefficient

The discomfort degree-hours coefficient was calculated for the hours when the indoor air temperature was below the minimum comfort air temperature in the Winter period. The difference between these two variables per hour allows the calculation of this coefficient for a period of the year.

$$Discomfort\ hour\ coefficient = \sum \left| T_{indoor} - T_{minimum\ comfortable} \right|$$

3 Characterization of the models used in the simulations

In order to determine and explore the impacts and thermal performance of particular solutions on windowsills and jambs, a simplified model was created. The temperature distributions and the heat exchanges were analysed for the interior space and the windowsill and jambs.

The simplified model used in the simulations includes just a single one room with an area of approximately 4 m by 4 m, a ceiling height of 3 m, and a single window. To reduce the number of potentially confounding factors, no other physical elements (e.g. doors, furniture, thermal bridges, etc.) or internal heat gains (e.g. from lighting, equipment or people), were considered. The geometrical model and nature of each surface was built and define within the Sketchup software package and then exported to Energyplus [Energyplus^{TM}, 2016]. The model's variables were then manipulated and set within EnergyPlus, including building materials, constructions, shading parameters, simulation periods. Given that Energyplus (and almost every other building simulation software packages) use representations of the 3D elements only through 2D surfaces, the model's geometry had to be defined in such a way that the windowsill and jambs would be explicitly included. As these elements are defined by the thickness of the wall, the model's geometry effectively projects the window to outside, placing the glass near to the outside surface of the wall, then connected to the main room volume through the windowsill and jamb surfaces as clearly visible in the model's image in Figure 3.

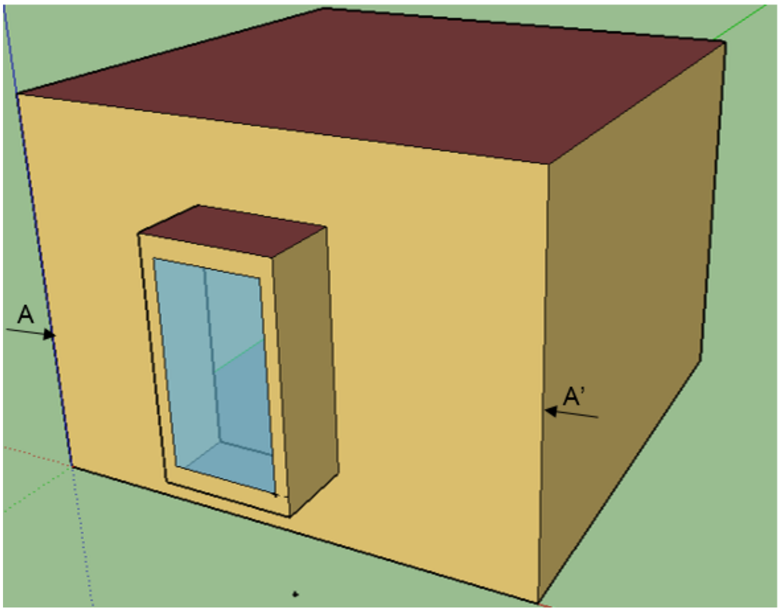

Figure 3.Building's sketch

3.1 Models variables

3.1.1 Period of the simulation

The simulation was divided into two different periods: winter and summer. The winter period encompasses the four months from January to April, while the summer period ranges from June to September.

3.1.2 Solar distribution

The parameter considered for the solar distribution was "full interior and exterior with reflections". This provides a way to determine the shading patterns in case of vertical and horizontal shading as well as blind shading. The parameter "full interior and exterior with reflections" assumes that the solar radiation is not totally absorbed by the ground. Instead, radiation spreads through the surfaces such as wall, floor and roof.

3.1.3 Convection and conduction

The algorithm used for the interior and exterior convection is named adaptive convection. Beausoleil-Morrison (2000, 2002) developed a dynamic algorithm that possesses several hc (surface exterior convective heat transfer coefficient) equations models suitable for various situations, which are then selected based on the specific situation at a certain time.

The method used in EnergyPlus™ for conduction transfer functions' (CTF) calculation is the state space method. The state space method uses an algebra matrix that can eliminate the state space variables that correspond to the nodal temperatures, and the final matrix is just a function of the inputs (outdoor temperatures). Consequently, the final matrix provides the heatfluxes (outputs).

CTF is a competent method to calculate surface heat fluxes, because with this method there is no need to know the temperatures and fluxes within the surface. None the less, if the time step decreases, CTF become unstable [Energyplus™, 2016].

3.1.4 Constructions

The four exterior walls and the ceiling are composed, from outside to inside, by 25 millimetres of stucco, 400 millimetres of stone, followed by 100 millimetres of insulation (expanded polystyrene) and 12 millimetres of plasterboard. The walls have 3 meters of height and 4 meters of length. The floor has a similar construction by includes an extra interior layer of wood. The properties of the materials used in the building are outlined in table 1 and table 2.

The window is considered a standard double-glazed window with two 6 millimetres layers of glass separated by a layer of air.

Material	Specific mass [kg/m^3]	Thermal conductivity [W/(mK)]	Specific heat [J/(kg.K)]
Stucco	1856	0.72	840
Stone	2560	3.17	790
Insulation	29	0.029	1210
Plasterboard	850	0.2	850

Table 1. Thermal properties of the materials used in the building's construction

Material	Thermal absorptance	Solar absorptance	Visible absorptance
Stucco	0.54	0.4	0.4
Stone	0.45	0.5	0.5
Insulation	0.9	0.25	0.25
Plasterboard	0.9	0.6	0.7

Table 2. Optical properties of the materials used in the building's construction

3.1.5 Tested materials

A number of materials were tested to determine their performance as elements to offer thermal inertia to a space when applied to the windowsill and jambs, namely wood (as a representation of a common option), cork and plasterboard (as low mass materials), and granite, brick, slate and marble (as highly massive materials). The thickness used for this elements was 2 cm in all the cases.

The properties of all materials are shown in the table 3 and table 4:

Absorbing Material	Specific mass [kg/m^3]	Thermal conductivity [W/(mK)]	Specific heat [J/(kg.K)]
Wood	592	0.09	1170
Cork	150	0.0385	2000
Plasterboard	850	0.2	850
Granite	2915	2.65	807.5
Brick	1920	0.89	790
Slate	2750	1.65	870
Marble	2785	5.5	870

Table 3.Thermal properties of the materials used

Absorbing Material	Thermal absorptance	Solar absorptance	Visible absorptance
Wood	0.95	0.7	0.7
Cork	0.89	0.45	0.45
Plasterboard	0.9	0.7	0.7
Granite	0.45	0.55	0.55
Brick	0.93	0.68	0.68
Slate	0.87	0.87	0.87
Marble	0.95	0.44	0.44

Table 4.Optical properties of the materials used

3.1.6 Definition of the different models

A number of models were tested to verify the impact of some building characteristics in the potential of the solutions here investigated:

- two different window sizes (1.5 m and 2 m tall, both at 1 m wide)
- two orientations (south-facing and southwest-facing).

The four possible combinations of these two variables define 4 of the models used, namely:

- Model A – 1.5 m tall window; South-facing;
- Model B – 2 m tall window; South-facing;
- Model C – 1.5 m tall window; Southwest-facing;
- Model D – 2 m tall window; Southwest-facing;

3.1.7 Models to test the impact of direct radiation

Two further models were used to test a condition where the effect of direct solar radiation in the test surfaces is excluded. This was achieved by placing the testing materials in another area of interior wall of the room and replacing the windowsill and jambs with the wall materials. The chosen areas were placed on the East and West walls, the ceiling and the floor, in order for the materials to be in similar positions to the ones they stood on when placed in the windowsill and jambs.

Apart from the positions of the testing materials in the rooms, these 2 models, named Model X and Y, are comparable to Models A and B in every other respect.

3.1.8 Shading

Depending on the season, the window shading algorithms were defined in two distinct ways. A fully opaque shutter is used in the winter period from 0 am to 7 am. While in the summer period, the building’s shadings are operated automatically, closing whenever the indoor temperature exceeds 23 degrees.

3.1.9 Location and local climate

The location used for the simulation is Porto. Portugal is located within an area of the globe which is under temperate Mediterranean climate conditions. The south of Portugal, mainly the Algarve, is the country’s region that shares the most characteristics (climate and weather related) to the rest of Mediterranean Europe. The weather conditions become more distinct, as latitude increases: winters are colder and rainier. This is partly explained by the long coast that stretches throughout the western part of the country, and the closeness some coastal cities have to the sea. In case the distance to the Atlantic Ocean was larger, the climate would have a higher thermal gradient and less precipitation. Portugal is one of the European countries with the mildest of weathers.

Porto is located within the portuguese northern coastline. This means that its weather is highly influenced by its proximity to the sea, which translates into several rainy days all year round and a smaller number of dry months. The thermal year gradient is fairly low.

3.1.9.1 Winter period:

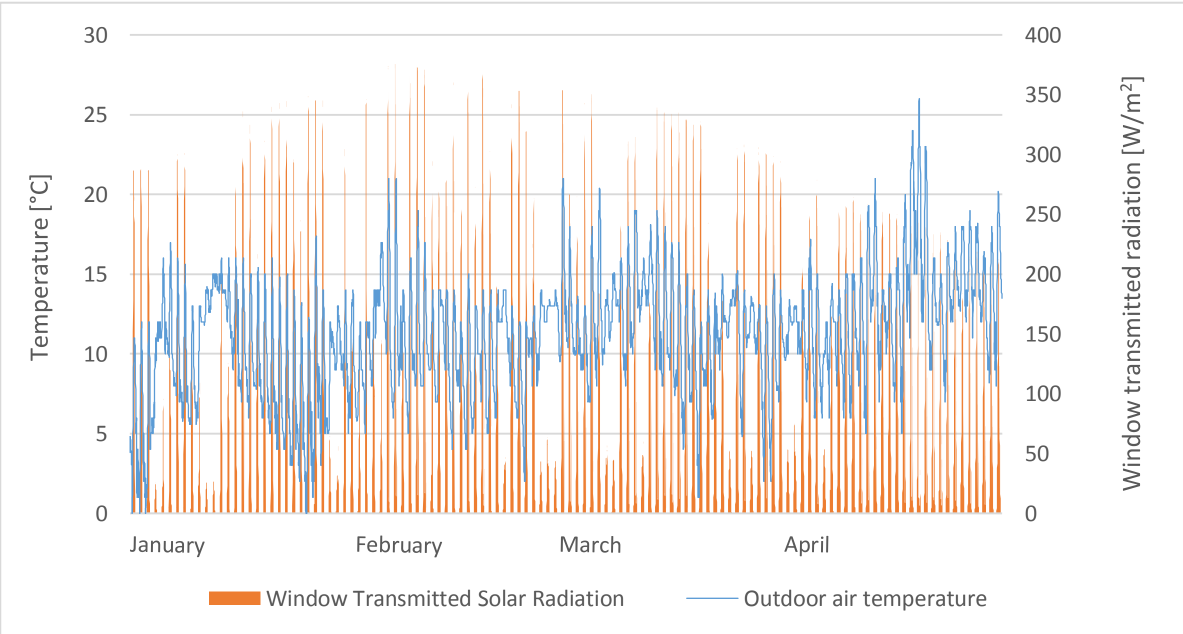

Figure 4. Outdoor air temperature and window's transmitted radiation in the winter period

In the winter period the outside temperature varies from 0 to 25°C (Figure 4). The radiation that enters the building through the window has an average value of 74.29 W/m².

3.1.9.2 Summer period:

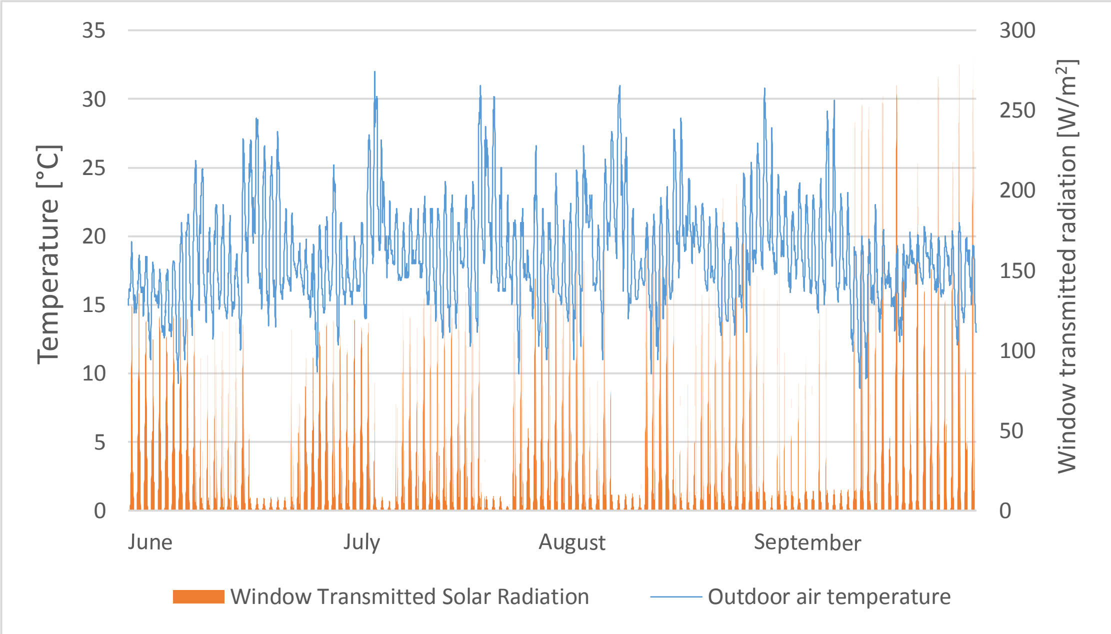

Figure 5.Outdoor air temperature and window's transmitted radiation in the summer period

In the summer period, the outdoor air temperature varies from 10 to 32°C (Figure 5). Due to the automatic shading devices in the window, the solar radiation that effectively enters the building has a low average value of approximately 18 W/m^2, showing that these are working as expected and protecting the building from overheating due to excessive solar gains.

4 Results of the simulations

4.1 Base Model

As a means to comparing a number of alternatives, a base case model (base model) was set, for which the simulation results are presented below. The base model is defined for both A and B geometries (i.e. with 1.5m tall window and 2m tall window, respectively) and employs the commonly used wood material in the windowsills and jambs.

The results feature:

- the indoor air temperatures during the winter and summer periods as well as a more detailed view of specific days within those periods;
- the radiation heat gain absorbed by the main surfaces;
- the test of the model's orientation (by comparison to geometries C and D) and how it can affect the indoor air temperature and the incident radiation;
- the analysis of the indoor comfort temperature.

4.1.1 Indoor air temperature during each period

The first two charts (Figure 6 and Figure 7) show the evolution of the indoor air temperature in two distinct periods: winter which corresponds to the months of January to April, and the summer period which encompasses the months of June to September.

4.1.1.1 Winter period

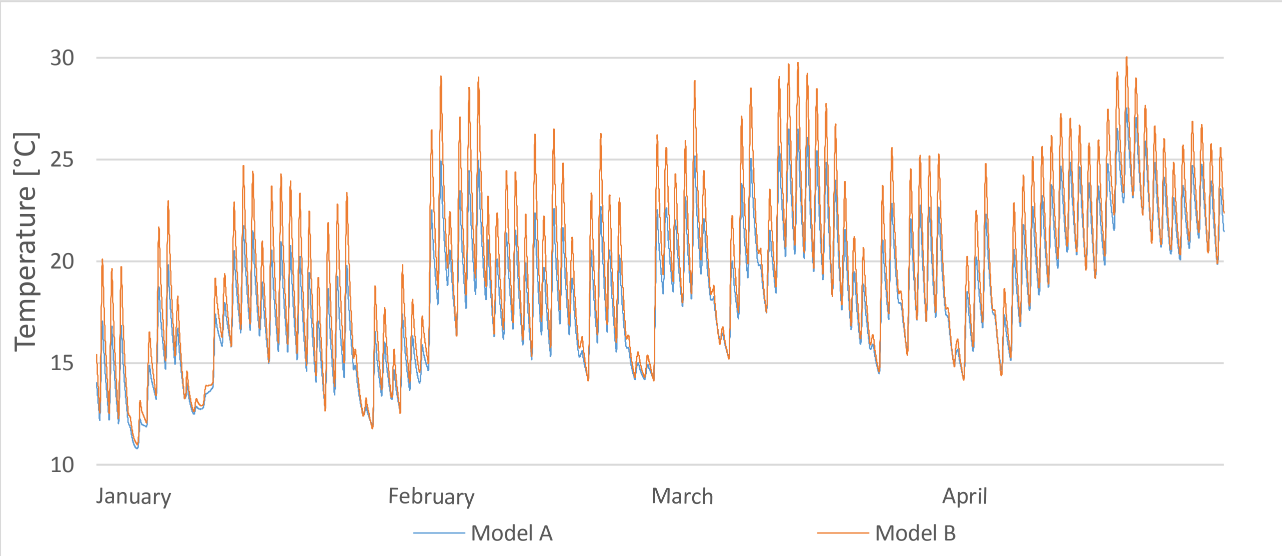

Figure 6. Indoor air temperature during the winter period: Model A and B

The indoor air temperature in the winter period for both models A and B varies between approximately 11 to 30°C. However, the thermal amplitude over the clearly seen daily cycle is higher in model B. This is probably due to the larger window surface area which collects more sun during the day but during the night presents higher thermal losses. So, on average, both models tend to follow the same trends but model B might offer slightly more comfortable conditions during the day. Conversely, even during the winter time, the model with the largest window frequently suffers from overheating, with temperatures frequently going above 25°C. During the winter simulations, the window shading algorithm operates only during the night time, from 0am to 7am and, thus, during the day, it does not check if the building might be overheating (as is the case for the summer simulations). As expected, the indoor temperatures are lower in the coldest months of January and February.

4.1.1.2 Summer period

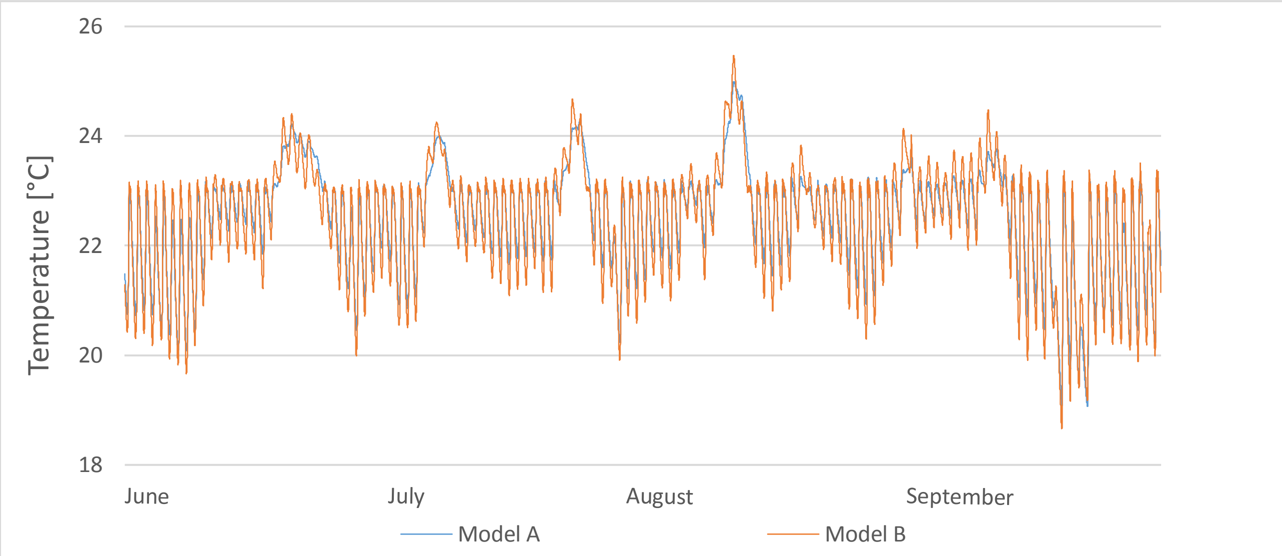

Figure 7. Indoor air temperature during the summer period: Model A and B

In the summer period, the indoor air temperature has a more stable behaviour throughout all 4 months and for both models. This is mainly due to the external shading devices being activated when indoor air temperatures go higher than 23°C. This effectively acts as a semi-passive system controlling and avoiding excessive solar heat gains. Air temperatures show how these devices are operating correctly and as expected. There are only a handful of situations when indoor temperatures go above the 23°C mark but these are not a result of solar heat gains (analysed in further detail below).

4.1.2 Indoor air temperature for the coldest day of the year: 2nd of January

In the charts below (Figure 8 and Figure 9) show a detailed view of the coldest day during the winter period, in this case 2nd of January.

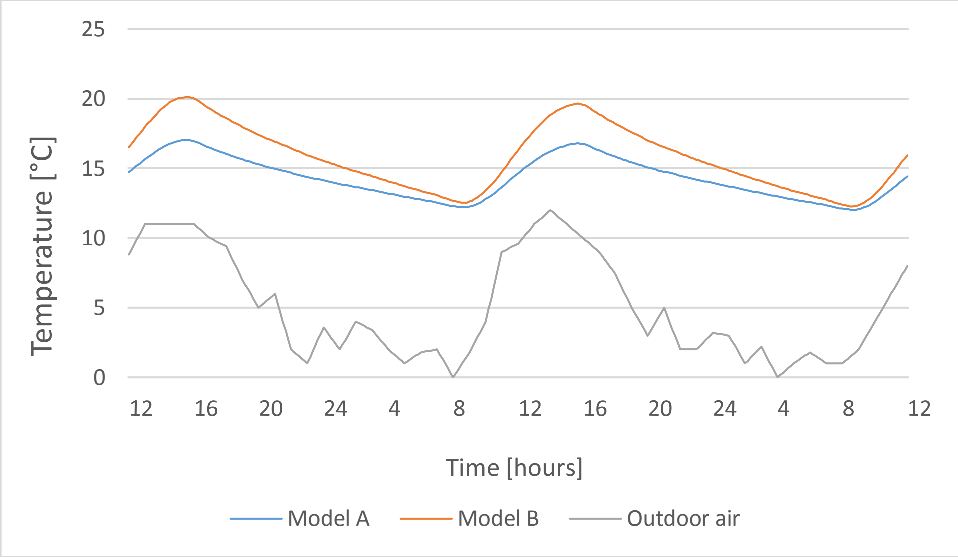

Figure 8.Outdoor air temperature and indoor air temperature for the base model for a period of 48 hours, including the coldest day of the year

Outdoor air temperatures on the 2nd of January, reach 0°C in the early morning hours and climb to just over 10°C around midday. As observed previously, indoor air temperatures during the day tend to go higher for the model with the largest window area, i.e. model B. However, as soon as the sun goes down, indoor temperatures also decrease for both models and reach an almost similar value during the coldest hours. At this point, both models would have uncomfortable conditions for the occupants. Nonetheless, it must be recalled that in these simulations, no internal gains or any other heat sources were considered. Still, the model with the largest windows, does show some periods of comfort conditions even in this worst-case scenario, demonstrating that fully passive performance is not very far off.

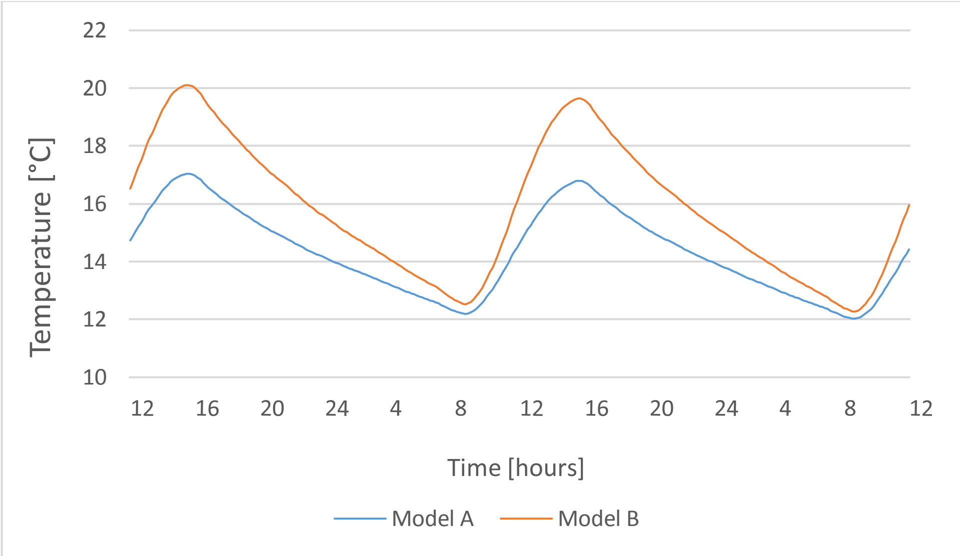

Figure 9. Indoor air temperature for the base model for a period of 48 hours, including the coldest day of the year

This "zoomed in" version of Figure 8, reveals that although the temperatures for the two models start at around the same point, approximately 12.5°C at 8 am (2nd of January), model B reaches higher indoor air temperatures than model A. The largest difference between the two models corresponds to 3°C.

4.1.3 Indoor air temperature for the hottest day of the year: 10th of August

Figure 10 demonstrates the evolution of the indoor air temperature and the outdoor air temperature for the hottest day of the year. To get a better understanding of what happens in this specific day, the graph also shows the 12 hours before 0 am on 10th of August and the 12 hours after the end of that same day, which correspond to the first 12 hours of the 11th of August.

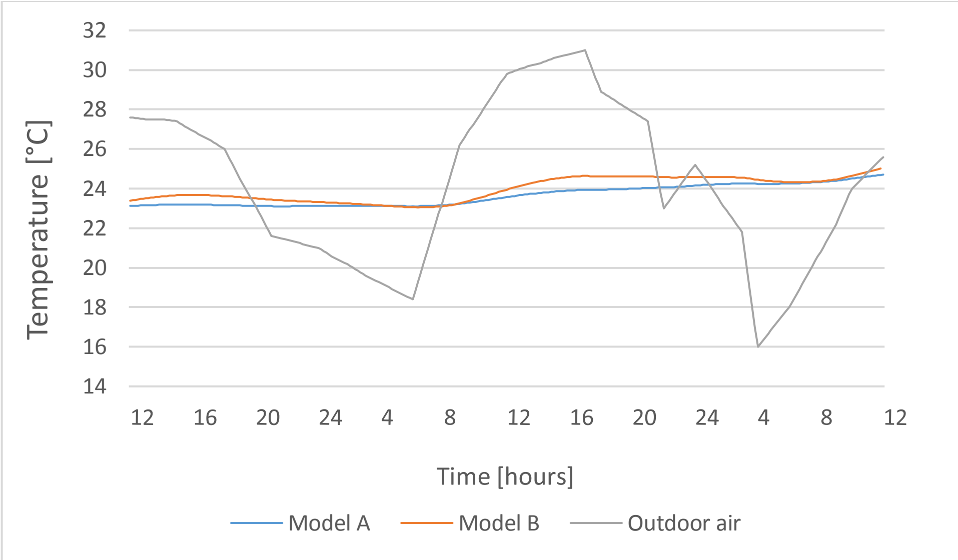

Figure 10. Outdoor air temperature and indoor air temperature for the base model for a period of 48 hours, including the hottest day of the year

Although the outdoor air temperature varies from 16°C to 31°C, the indoor air temperature for the two models maintains its values within a small interval, between 22°C and 25°C. For a deeper analysis, the chart shown above (Figure 10) is zoomed in below (Figure 11). It includes only a representation of the indoor air temperature.

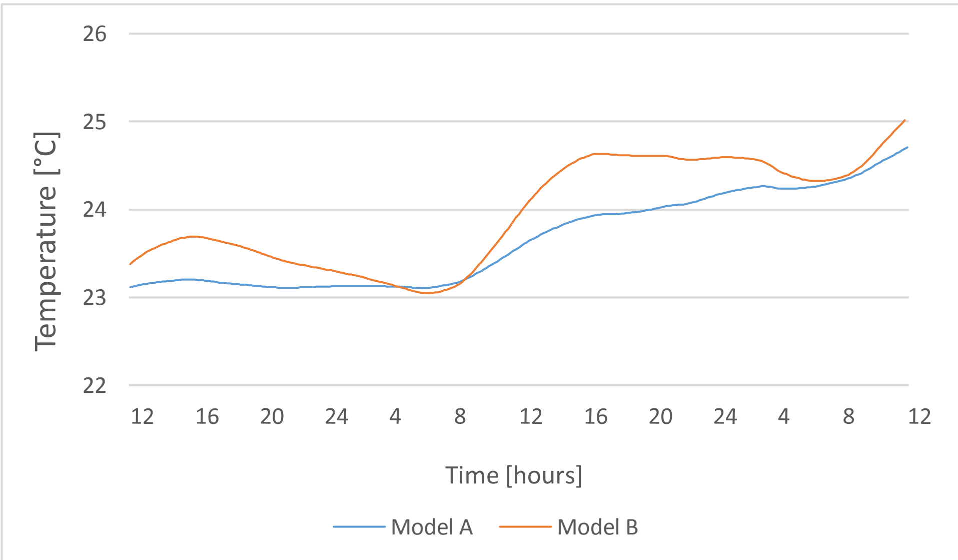

Figure 11. Indoor air temperature for the base model for a period of 48 hours, including the hottest day of the year

Figure 11 displays the minor variation in the indoor air temperature previously mentioned, which can be justified by the fact that the shading device is on during this entire period, thus blocking all incident solar radiation. The difference in indoor temperature for both models is justified by the fact that model B loses 9 W/m^2 by conduction between the 10^{th} and 11^{th} August, while model A gains 21 W/m^2.

4.1.4 Indoor air temperature for the largest difference between the outdoor and indoor air temperatures

Apart from studying the hottest and coldest day of the year, it was also relevant to learn more about the days when the interval between the outdoor and indoor air temperature is the largest. The graphs below (Figure 12 and Figure 13) show the days with these characteristics for the winter and the summer period.

4.1.4.1 Winter period: 20th of March

The most visible difference is the distance between the outdoor temperatures and the indoor air temperatures for the two models. The largest difference between the indoor and outdoor temperature is approximately 15°C, which happens at 4 pm on March 20th for the indoor air temperature, model B.

In order to have a better understanding of what happens with the indoor air temperature in both models, the previous model was zoomed in, which resulted in the exclusion of the outdoor air temperature.

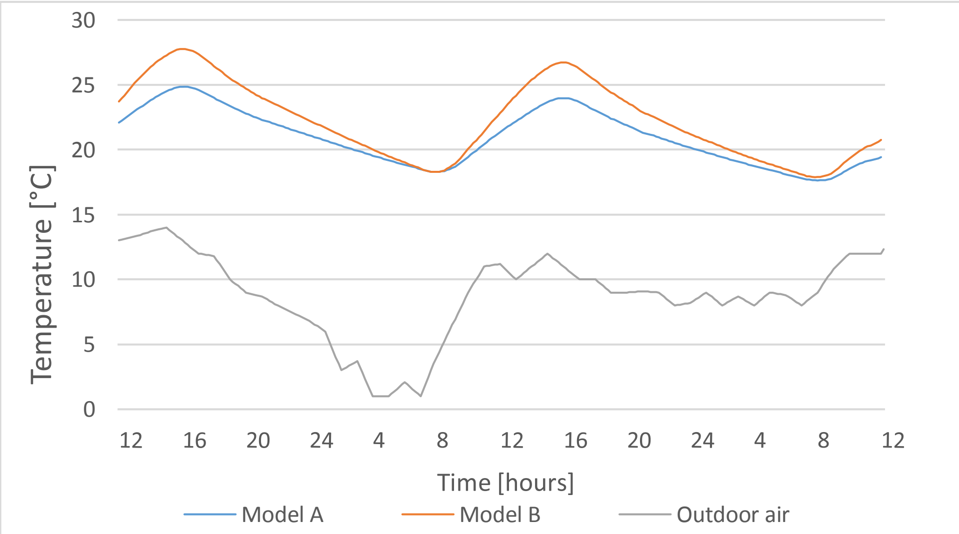

Figure 12. Outdoor air temperature and indoor air temperature for a period of 48 hours, including the day with the highest interval between the outdoor and indoor temperature for the winter period

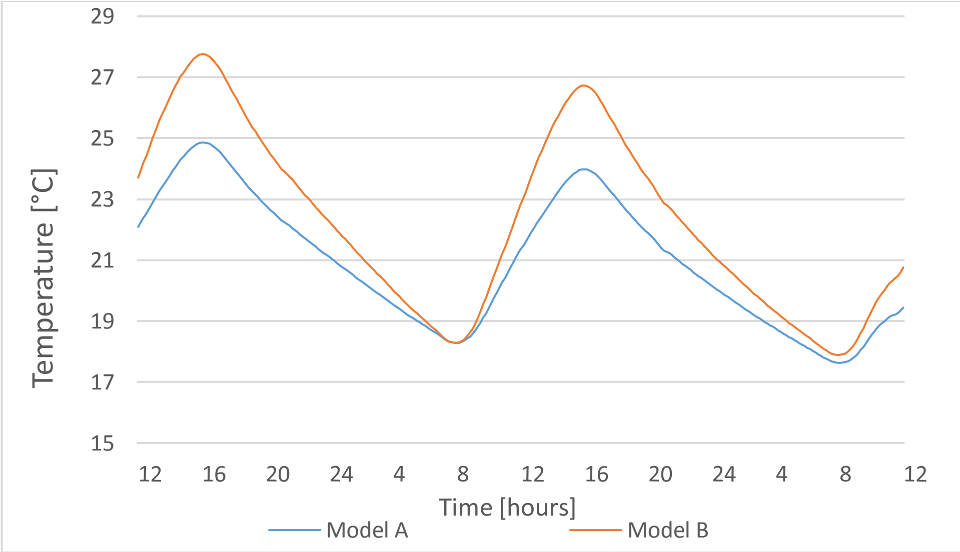

Figure 13. Indoor air temperature for a period of 48 hours, including the day with the highest interval between the outdoor and indoor temperature for the winter period

By 20th of March the weather already tends to show warmer days outside. The radiation which gets inside the building is also larger because the sun is on a higher position and days are longer. These two reasons can justify why the indoor temperatures are generally higher than what had been previously observed for the coldest day of the year (i.e. 2nd of January). However, the largest difference between model A and B happens at 4 pm for the two days and corresponds to approximately 3°C. At this point, indoor temperatures are already getting too high in Model B, thus showing that shading would already be required to control the excessive solar heat gains.

4.1.4.2 Summary period: 13th of September

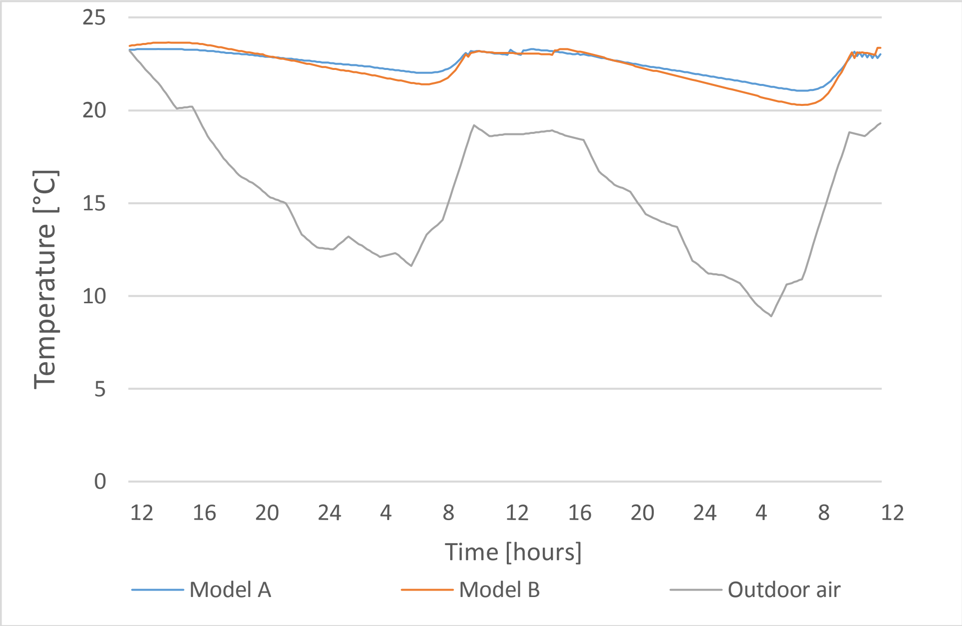

Figure 14. Outdoor air temperature and indoor air temperature for a period of 48 hours, including the day with the highest interval between the outdoor and indoor temperature for the summer period

In this section, the summer day with the highest interval between the outdoor and indoor temperature is analysed. Although the temperature in the first point of the graph (Figure 14) (t=12 hours) is closely same for both situations, after a couple of hours the outdoor temperature decreases significantly. Indoor temperatures, however, change much less, resulting in a thermal amplitude of about 2 to 3ºC throughout the day.

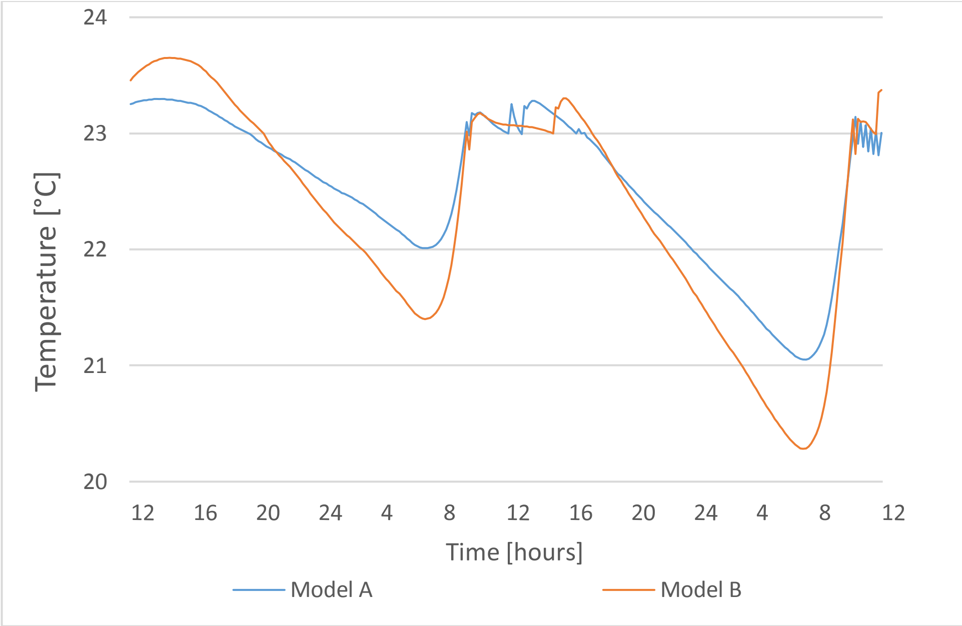

Figure 15. Indoor air temperature for a period of 48 hours, including the day with the highest interval between the outdoor and indoor temperature for the summer period

In the “zoomed in” version shown in Figure 15, the temperature for both models is similar, the major differences occurring after 6 am on 13th of September and 7 am on 14th of September. These periods are related to the beginning of a day. The 0.5°C difference happens because the area of the window in model B is larger than in model A, which causes a higher heat transfer between the inside and outside environment through the window. The impact of the shading device blocking solar radiation is also clearly visible whenever indoor temperatures go above 23°C. The short-time variations observed at this point are merely an artefact of the simulation software having a timestep of 10 minutes and, thus, cycling through opening and closing settings of the shading device.

4.1.5 Solar radiation heat gain and temperature in the absorbing surfaces

4.1.5.1 Winter period

The windows in models A and B are oriented towards south and, because of this, the surface that gets most radiation is the windowsill. Figure 16 shows how the windowsill behaves in terms of temperature and heat gain through solar radiation in the first three days of January.

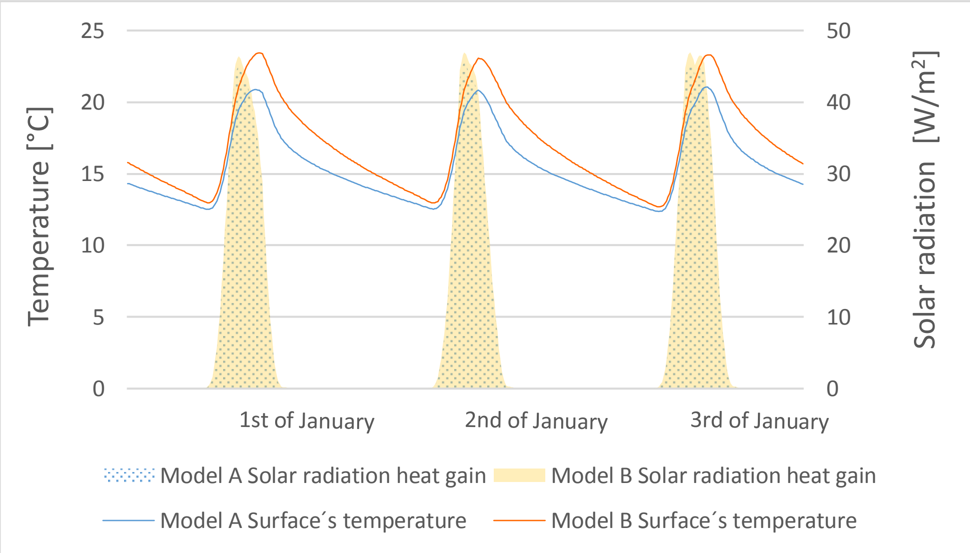

Figure 16. Windowsill surface's temperature and solar heat gain for a period of three days in the January: Base model

Model B receives more incident solar radiation than model A, albeit it being only by a small amount, and that is reflected on the temperature of the windowsill. The temperature of the windowsill in model B, when the radiation reaches its maximum value during the day, is 2 to 3°C higher than in model A. In the night period, the windowsill´s temperature reaches approximately the same minimum value in both models.

4.1.5.2 Summer period

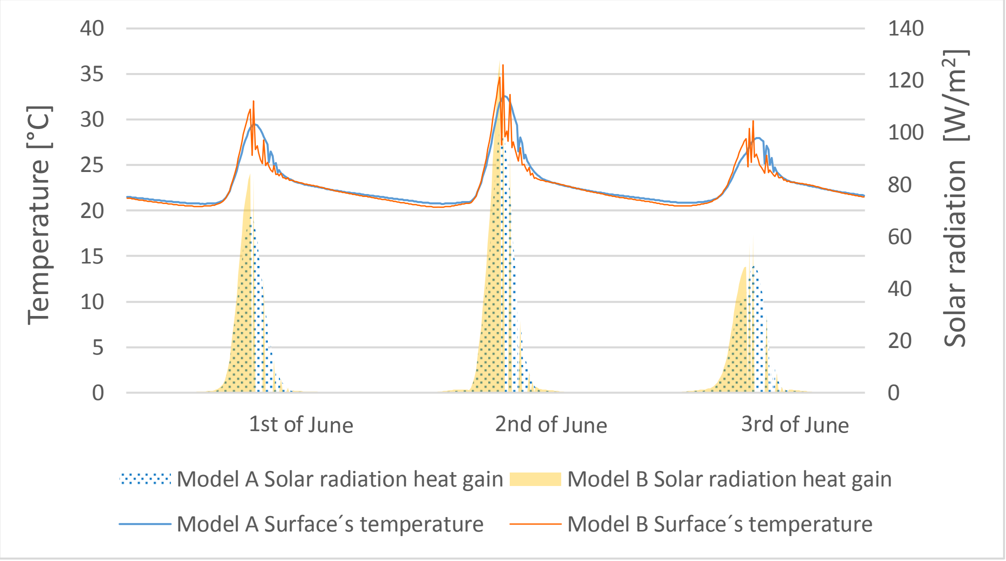

Figure 17.Surface's temperature and surface's solar heat gain for a period of three days in the June: Base model

In the first three days of June, the windowsill's temperature and incident radiation is similar for the two models. June 2nd is the day when the windowsill reaches higher temperatures, almost 35°C. This fact can be explained by the solar incident radiation that even though the solar shading starts to operate when the indoor temperature reaches 23°C, the windowsill still gains heat, which is 40 W/m^2 higher during June 2nd than in the 1st of June, and 60 W/m^2 higher than in the 3rd of June. The maximum solar incident radiation on the windowsill is 120 W/m^2.

4.1.6 Different window orientation

To test the impact of window orientation, two new models (C and D) were tested with an orientation towards southwest, i.e. rotated -45° in relation to models A and B. These two new models were simulated, and the results with different orientation but equal parameters for the other variables are presented below.

4.1.6.1 Indoor air temperature and incident solar radiation for the coldest day of the year

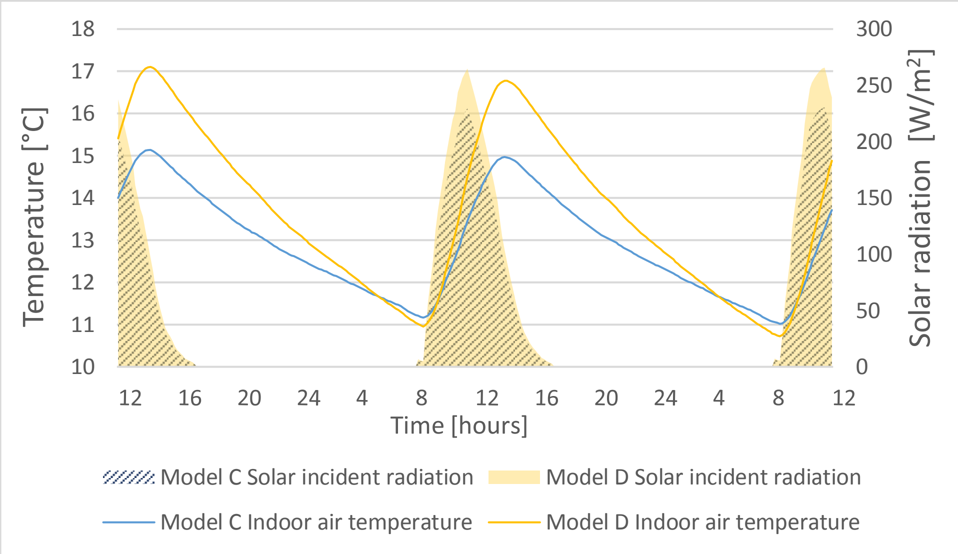

Figure 18. Indoor air temperature and solar incident radiation for a period of 48 hours, including the coldest day of the year

The indoor temperatures in these two models are not as high as the temperatures that can be reached in models A and B. In models A and B the indoor temperatures can increase up to 20°C and in the models C and D the maximum is 17°C. This fact shows that the amount of solar incident radiation entering the space is smaller since the building is not facing south, which consequently does not enable the indoor space to get warmer. 5695 W/m^2 is the total incident radiation for model C during the 2nd of January, which is 2170 W/m^2 lower than for model A. In model D, the total of incident radiation that enters the building is 6563 W/m^2, which is 2503 W/m^2 lower than for model B.

4.1.6.2 Indoor air temperature and incident solar radiation for the hottest day of the year: 10th of August

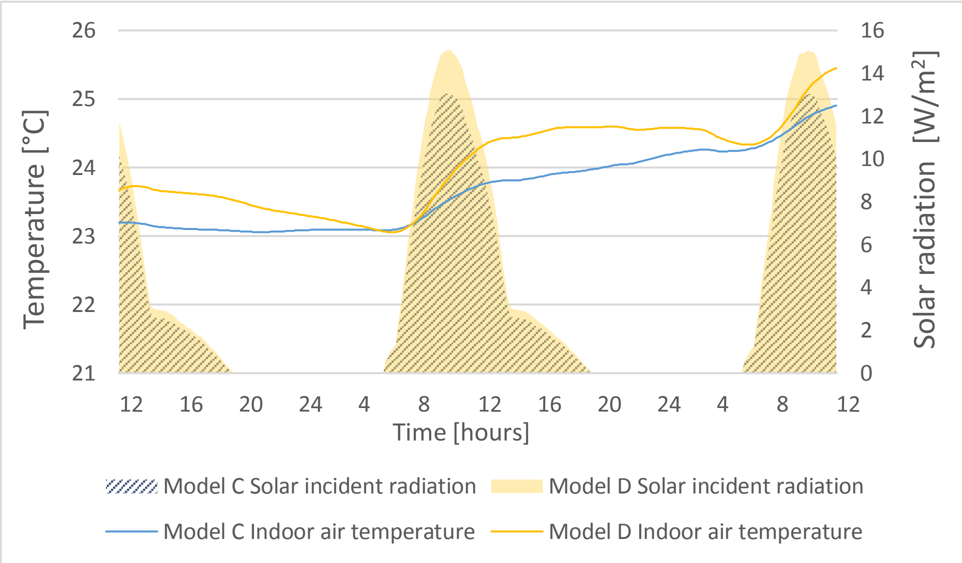

Figure 19. Indoor air temperature and solar incident radiation for a period of 48 hours, including the hottest day of the year

In this case, the indoor air temperatures for models C and D are very similar when compared to the indoor temperatures for models A and B. Despite the activation of the shading devices, the model with the largest window area still allows the entrance of a higher amount of solar radiation, which makes the building warmer.

The 10th of August is the hottest summer day, dictating that the shading devices are activated most of the time. In fact, during the 48 hours shown in the charts, the indoor air temperatures are always above 23°C. Between the 10th and the 11th of August the room in model D is losing a total of 9 W/m^2 by conduction, and Model C is gaining 31 W/m^2 which explains the decreasing of the indoor temperature in model D.

Comparing the quantity of radiation that enters the window on August 10th to the 2nd of January, it is visible that the amount is much lower in August. The total incident radiation on the 10th of August for model D is 538 W/m^2 and for model C is 467 W/m^2 which corresponds to a difference of almost 100 W/m^2.This can be justified by the fact that during the summer period the shading device is always on when the indoor air temperature is greater than 23°C.

4.1.7 Comfort analysis

A comfort analysis was done for the base model for the two periods of winter and summer, and for two situations: a window with 1.5 meters of length (model A) and door/window with 2 meters of length (model B).

The results are summed up on the tables as: number of discomfort hours (and the corresponding number of days), and as degree-hours of discomfort. The table shows the percentage of days and number of hours, on which the interior temperature **was not** within the interval of the acceptable comfort temperature.

The temperatures' comfort interval was calculated based on the average of the outdoor air temperature for the thirty days prior to the day that is analysed. All these calculations were based on the adaptive method presented in chapter 2 and the acceptable limit of 90%.

Winter period	Uncomfortable Hours	Uncomfortable Days (%)	Discomfort degree hours (°C.h)
Model A	1668	58	5130
Model B	1684	59	6479

Table 5. Number of hours and days in which people would probably feel uncomfortable inside the building in the winter period: Base model

Summer period	Uncomfortable hours	Uncomfortable days (%)
Model A	148	5
Model B	222	7

Table 6. Number of hours and days in which people would probably feel comfortable inside the building in the summer period: Base model

During the winter period, the number of days analysed were 120. In 1668 hours in model A and 1684 hours in model B, people would probably feel uncomfortable inside the building. This corresponds to approximately 58% and 59% of the time for models A and B, respectively, which means that most of the time people would feel uncomfortable inside the building. The indoor temperature is below the minimum comfortable temperature for approximately 63 days in model A, while only in 6 days is it above the maximum comfortable temperature. This shows that just over half the time during the winter period people are uncomfortable because the indoor space is too cold.

While the difference between the two models is quite small, model B still shows a tendency to have slightly less comfortable conditions. This means that although there is more incident solar radiation in model B, this is not sufficiently high to warm up the space significantly more, and since the window's area is bigger, the thermal losses might overcome that effect.

The number of days analysed in the summer period were 122. The days when people felt comfortable inside the building corresponds to a percentage higher than 90% for both models A and B, meaning that the discomfort degree-hours are also low enough to be ignored. The high number of comfortable hours/days in the summer period can be explained by the fact that in most of the days the shading device was on, which means the temperature would not rise very much over 23°C. The average maximum comfortable temperature is approximately 26°C which means that when the shading device is activated the temperature will be close to 23°C, allowing the room to stay mostly under comfortable conditions.

4.2 The impact of different materials

After the presentation of base model details, the following results show the comparison between the base model which had wood as the absorbing surfaces' material, and the remaining models which had different materials for the windowsill and jambs such as cork, plasterboard, slate, brick, marble and granite.

4.2.1 Indoor air temperature for the coldest day of the year: 2nd of January

To follow a similar analysis to the base model, the graphs (Figure 20 and Figure 21) show how slate and marble perform in the coldest day of the year, because when these materials are used, the indoor air temperature has a similar performance to brick and granite. The base model with wood is present in all graphs in order to compare it to the other models.

Figure 20 demonstrates the indoor air temperatures for the two materials in question: wood and slate for both model A and B.

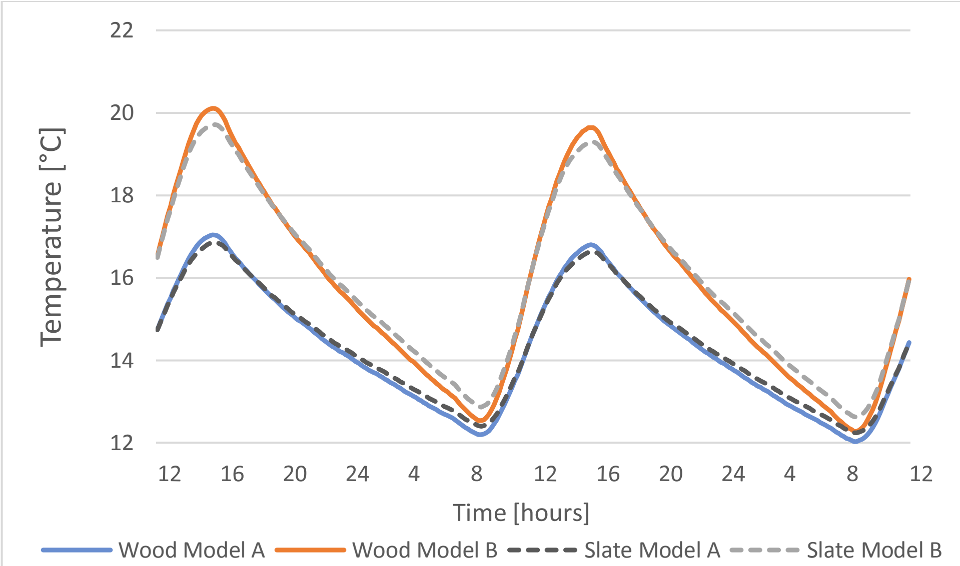

Figure 20. Indoor air temperature for a period of 48 hours including the coldest day of the year: Models A and B with Slate and Wood

The difference in the indoor temperature between the base models and the models with slate is not very large, but still visible. Even though the recorded differences in the graph (Figure 20) are less than 1°C when slate is used as the windowsill and jambs' material, the effect on the interior temperatures shows that thermal amplitude is lower, and temperatures do not reach as low or as high values. This is a characteristic behaviour of materials with higher thermal inertia.

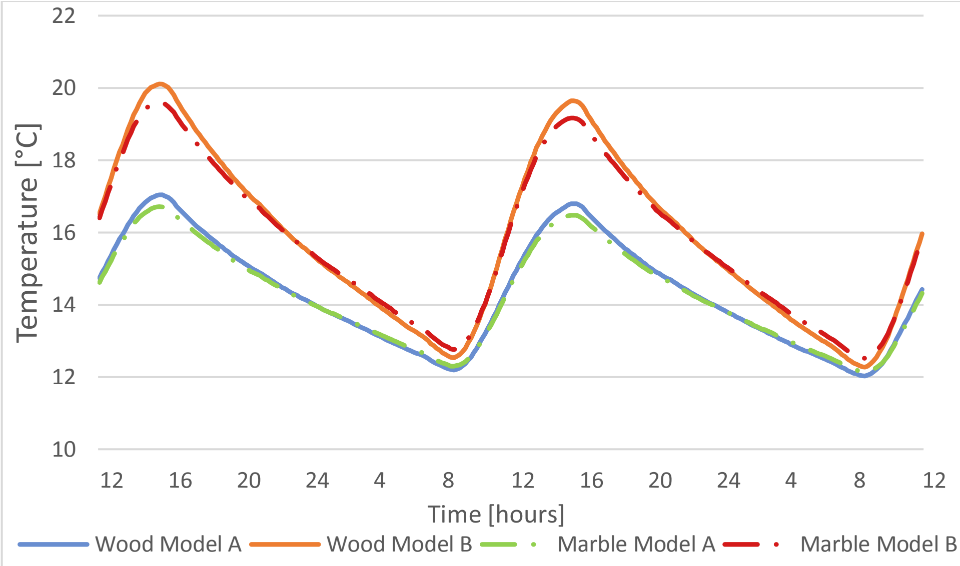

Figure 21. Indoor air temperature for a period of 48 hours, including the coldest day of the year: Models A and B with Marble and Wood

The graph above (Figure 21) shows that the indoor temperature's behaviour for when marble is used on the windowsill and jambs is similar to other high thermal materials, such as slate (Figure 20). When marble is used in the windowsill and jambs, temperatures are generally lower than when compared to slate, mainly because the value of solar and visible absorptance of marble is half of slate's solar and visible absorptance. On the other hand, marble's thermal conductivity is almost five times higher than slate's, but the fact that the windowsill and jambs are fairly thin (with only 2 cm) means that this difference has a very small contribution to the materials' performance.

4.2.2 Indoor air temperature for the highest interval between the outdoor air and indoor air temperature: 20th of March

The analysis for this topic is similar to the previous one, but a different situation is used. In this case, 20th of March is the studied day, which corresponds to the one when the indoor air temperature and outdoor air temperature have the most different values.

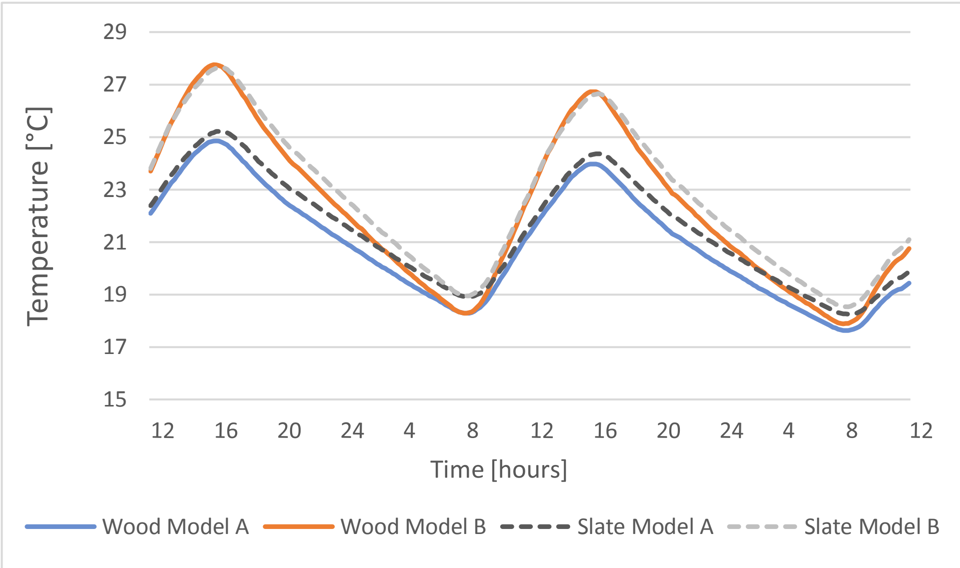

Figure 22. Indoor air temperature for a period of 48 hours, including the day highest interval between the outdoor and indoor temperature of the year: Models A and B with Slate and Wood

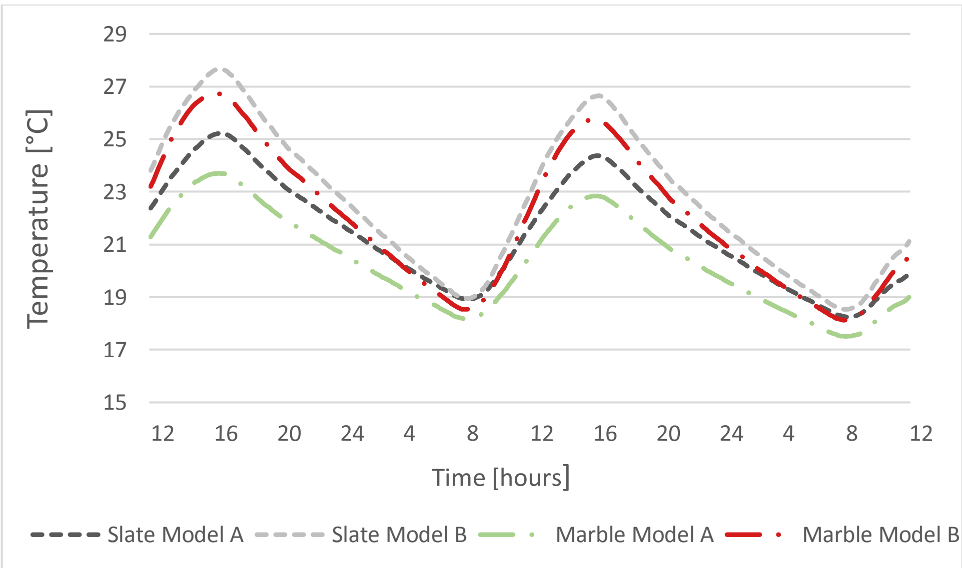

Figure 23. Indoor air temperature for a period of 48 hours, including the day highest gradient between the outdoor and indoor temperature of the year: Models A and B with Slate and Marble

The two materials chosen for this analysis are marble and slate, mainly because these are the solutions that both showed high mass but very different optical properties. The two graphs show a 48 hour period which corresponds to 12 hours before and after the 20th of March.

Figure 22 shows the indoor air temperature for wood and slate and for models A and B (different in window size). In both cases, when slate was used in the windowsill and jambs, the indoor temperature is always similar or higher than when wood was used. The most substantial difference happens at 8 am, corresponding to almost 1°C. Since this happens at the time when indoor temperatures are lowest, the use of slate in the windowsill and jambs shows a positive net effect towards helping to achieve indoor comfort conditions.

Figure 23 compares the indoor air temperatures between slate and marble, for both models A and B. Once again, it is observed that indoor temperatures are always higher in the cases where slate is used. The difference in the indoor temperature between marble and slate can get to 1.5°C.

4.2.3 Indoor air temperature for a week when the fluctuation in the outdoor temperature is lower: 24th of February to the 2nd of March

Instead of just choosing a 48 hour period or three days, a week is studied in this topic. The selected week includes 3 days which have low oscillations in their outdoor temperature. Slate, brick and granite which are high inertia materials are compared to wood, the base model. This week lies in the winter period and on the transition between two distinct months: February and March.

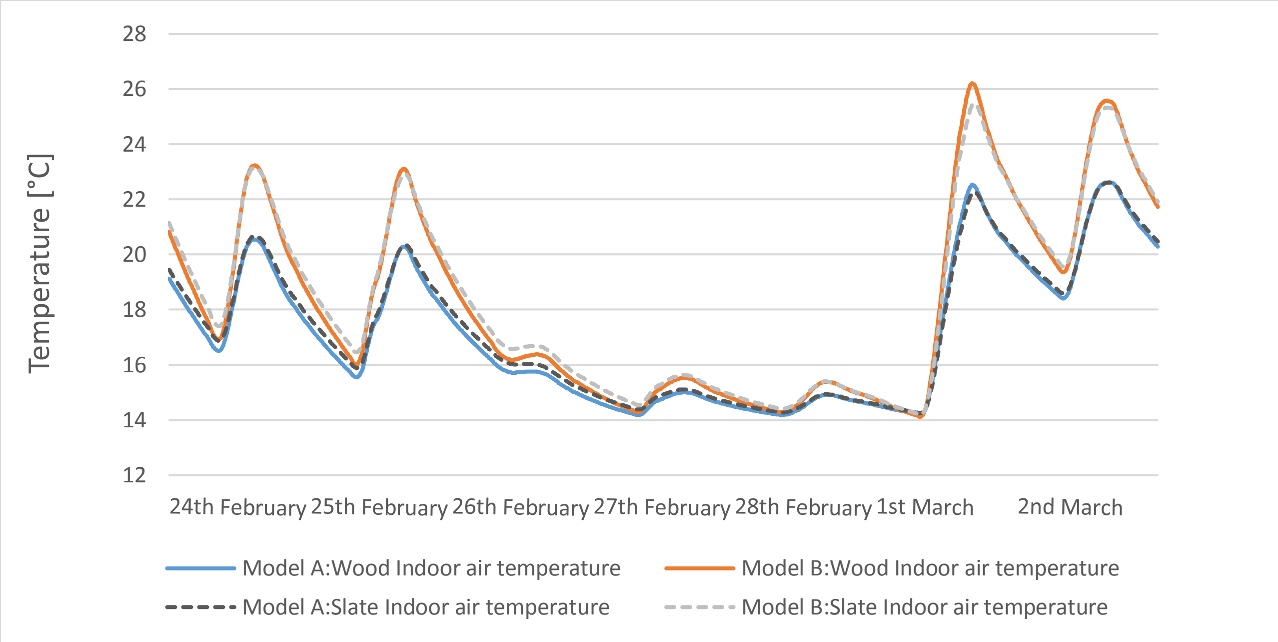

Figure 24. Indoor air temperature's behaviour from the 24th of February to 2nd of March: Model A and B with Wood and Slate

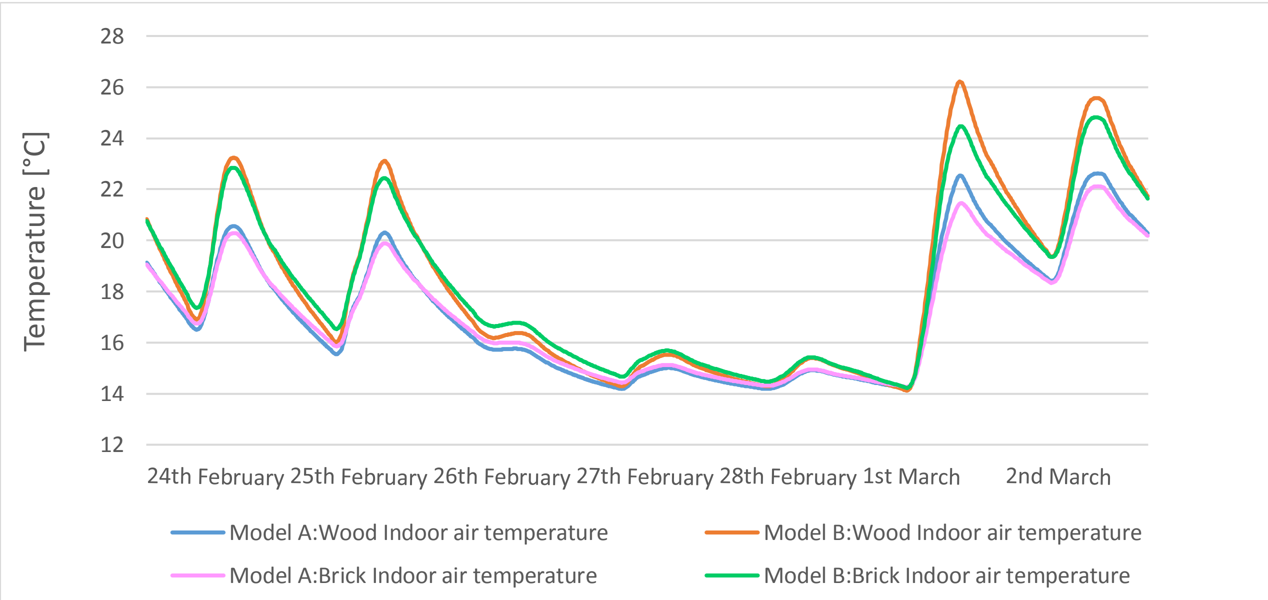

Figure 25. Indoor air temperature's behaviour from the 24th of February to 2nd of March: Model A and B with Wood and Brick

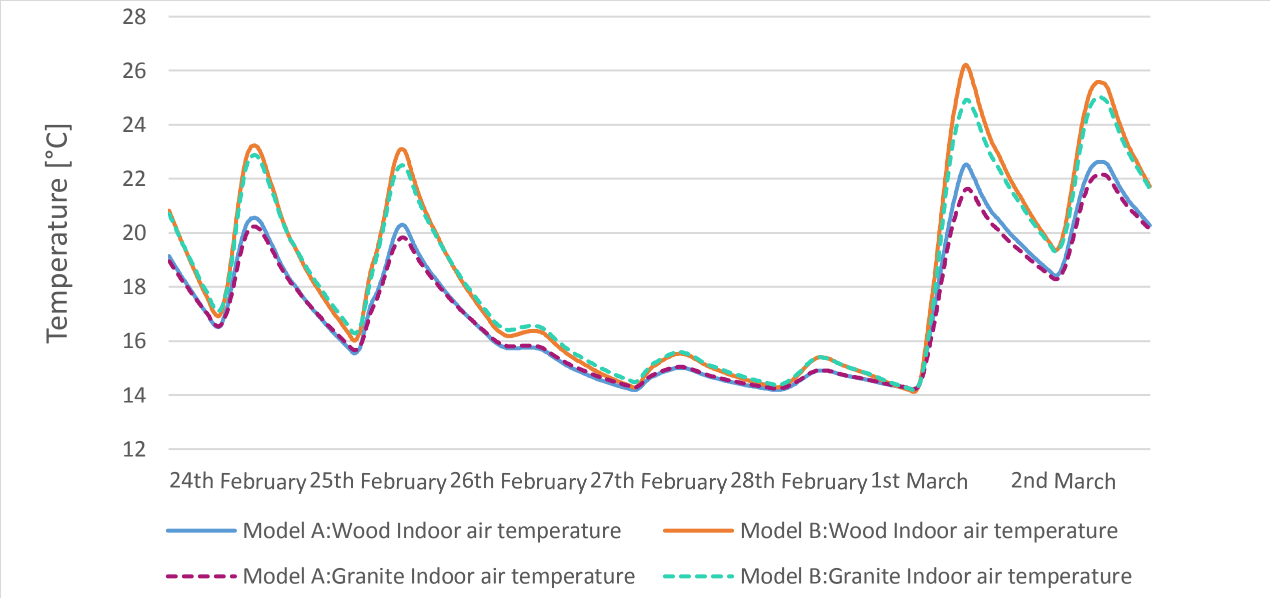

Figure 26. Indoor air temperature's behaviour from the 24th of February to 2nd of March: Model A and B with Wood and Granite

When the outdoor air temperature does not have major oscillations, the indoor air temperature for spaces with different materials in the windowsill and jambs is similar. The indoor air temperature has the same behaviour when slate or wood are used in the windowsill and jambs. This might also be a result of reduced solar radiation impinging on the surfaces, as these days tend to be overcast.

The set of materials which cause more differences in the indoor air temperatures are wood and brick. In the 1st of March, when the temperatures reach their peaks, the difference between them is almost 2°C. Brick is a material that does not have a positive influence on the indoor temperature performance during this week. Besides brick, and although granite can reach higher temperatures, when the lowest temperatures are analysed, they are similar for buildings with wood or granite as the windowsill and jambs' material.

4.2.4 Solar radiation heat gain and temperature in the absorbing surfaces

Since slate is the high thermal inertia material with the best influence on the behaviour of the indoor air temperature, it was selected for this topic as the material to be compared to the base model. As explained before, when the building is facing south, the windowsill becomes the surface which gets the highest amount of incident solar radiation, resulting in larger heat gains for the windowsill. The chosen days were the same ones analysed on the base model. In order to have a better understanding of the graphs, model B was represented for the two different windowsill and jambs' materials.

4.2.4.1 Winter period

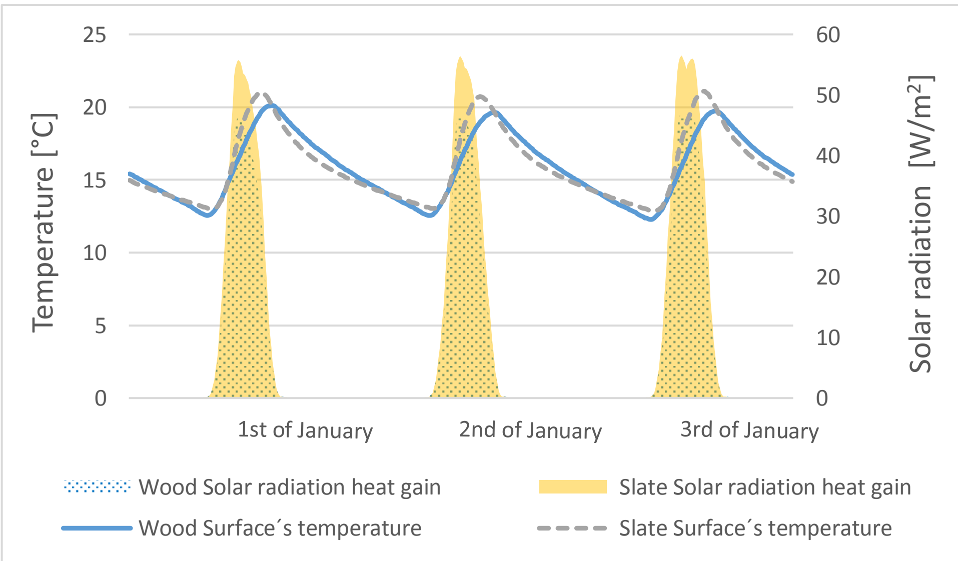

Figure 27. Surface's temperature and surface's solar heat gain for a period of three days in the January: Model B with Wood and Slate

The windowsill using slate absorbs more solar radiation than the one built with wood. The greater amount of radiation absorbed by the slate's windowsill can be explained by the slightly different optical properties such as solar and visible absorptance it possesses. The properties' values for the two materials differ in 0.17 in both solar and visible absorptance which explains the 8 W/m^2 difference in solar heat gains by the surfaces.

The windowsill's temperatures follow the same tendency as the solar heat gains, and, consequently, the windowsill's temperature when slate is used is higher than when wood is applied.

4.2.4.2 Summer period

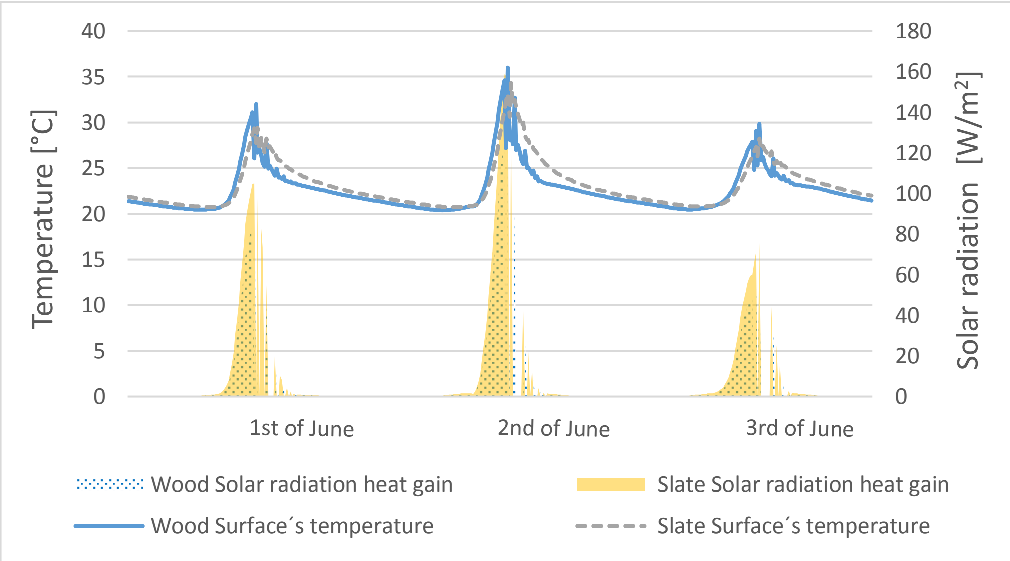

Figure 28. Surface's temperature and surface's solar heat gain for a period of three days in the June: Model B with Wood and Slate

In the summer period, the solar heat gains suffer fluctuations, because the shading device is activated when the indoor air temperature is higher than 23°C. This means the radiation heat gains are only received indirectly in this situation. The sill's temperature can reach 35°C which is 12°C higher than the indoor air temperature for the standard shaded situation. In the 1st of June and the 3rd of June the wood's windowsill gets hotter than the one with slate. This case can be explained by thermal properties since optical properties would contribute for the slate's windowsill to be warmer.

The thermal properties which present the most variation are specific mass and specific heat. In order to analyse just one property, the volumetric specific heat was determined. This property can be obtained by multiplying the specific heat by the specific mass. The volumetric specific heat calculated for wood was 692.64 kJ/ (m^3K) and for slate was 2393.5 (kJ/m^3K). Wood's volumetric specific heat is almost 3.5 smaller than slate's value. This means 3.5 less energy is needed to warm up the wooded windowsill than when slate is used. This is probably the reason why slate's windowsill temperature is lower than the wood's windowsill temperature.

4.2.5 Different orientation

4.2.5.1 Indoor air temperature and incident solar radiation for the coldest day of the year: 2nd of January

The windowsill and jambs' materials picked for the studied topic are plasterboard, brick and slate. They are compared to the base model which has wood as the windowsill and jambs' material. The 48 hour time interval corresponds to 12 hours before, after and during the 2nd of January. In the three situations shown by the graphs (Figure 29, Figure 30 and Figure 31) the building was rotated -45° facing Southwest, which influences the amount of solar radiation that enters the building. In order to have a better understanding of the graphs, model D was represented for the two different windowsill and jambs' materials.

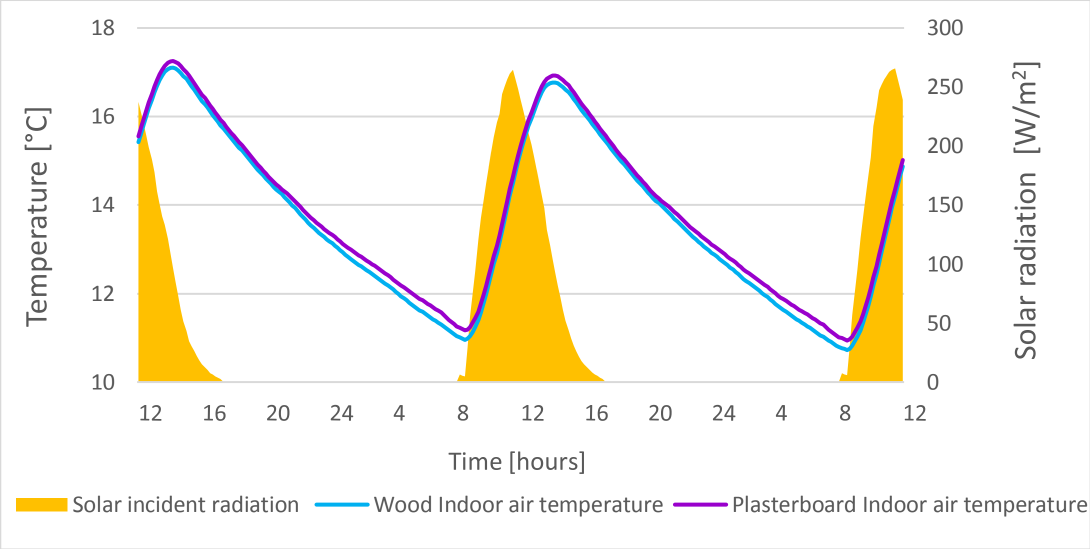

Figure 29. Solar incident radiation and indoor air temperature for a period of 48 hours, including the coldest day of the year: Model D with Wood and Plasterboard

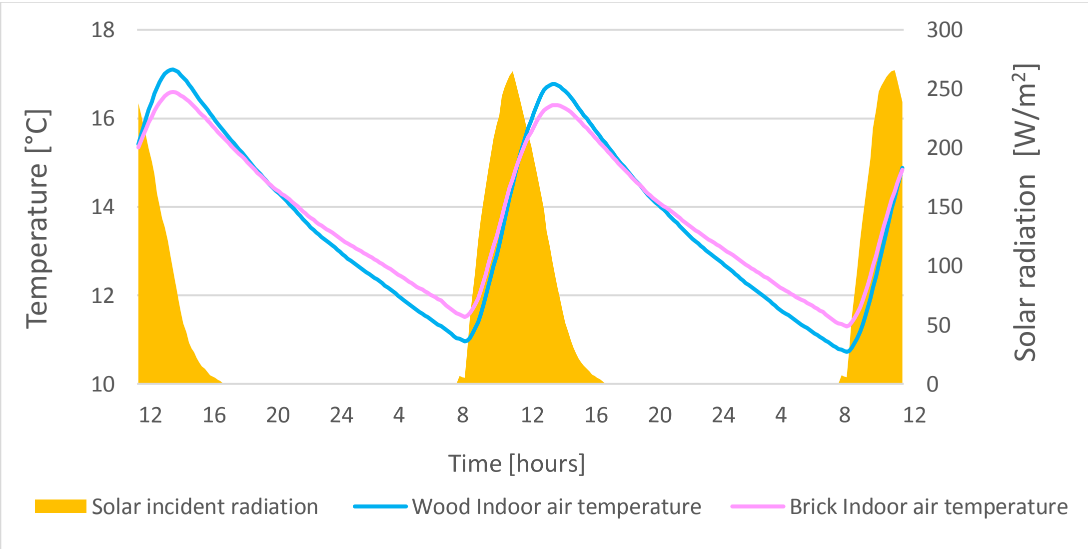

Figure 30. Solar incident radiation and indoor air temperature for a period of 48 hours, including the coldest day of the year: Model D with Wood and Brick

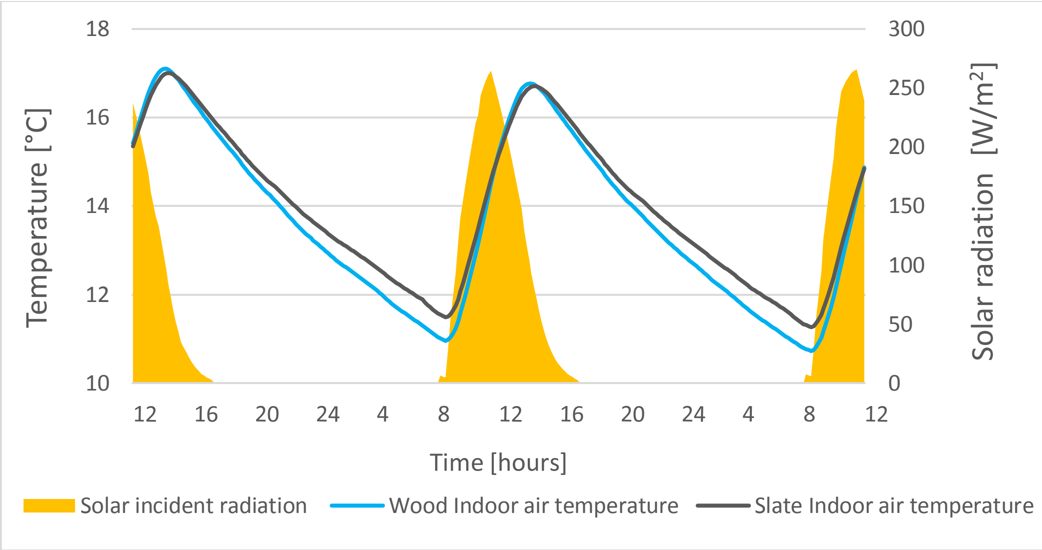

Figure 31. Solar incident radiation and indoor air temperature for a period of 48 hours, including the coldest day of the year: Model D with Wood and Slate

Figure 29 featuring plasterboard shows that wood and plasterboard are materials that cause the same impact in the indoor air temperature. Both materials are classified as low thermal inertia, which means that they do not have the capacity of storing a significant amount of the energy that they receive. This fact can justify the higher oscillation in the indoor temperatures.

Figure 30 shows the behaviour of the indoor air temperature when the windowsill and jambs' material is brick. The oscillations present in the first graph are diminished since brick has a better capacity to absorb energy and release it slowly. This can be noticed in two distinct situations graphically: when the temperature reaches its minimum during the night and when the temperature reaches its maximum at 2 pm in the 1st and 2nd of January. During the night, when brick is used as the windowsill and jambs' material the indoor temperature does not decrease as much as the indoor temperature when wood is used and, consequently, the indoor air space is warmer and more comfortable. When the temperature reaches its maximum at 2 pm in both days, the indoor temperature is higher for the space where the windowsill and jambs are built with wood.

Figure 31 shows an advantage that the windowsill and jambs built with slate has when compared to the one built with brick: when the maximum temperatures are reached, the room which features slate can get to higher values than the one with brick. These temperature values are similar to the ones reached with wood. This shows that slate is a better alternative to brick, because it can maintain the indoor temperature in the winter with higher and warmer values during the day and night.

4.2.5.2 Indoor air temperature and incident solar radiation for the hottest day of the year: 10th of August

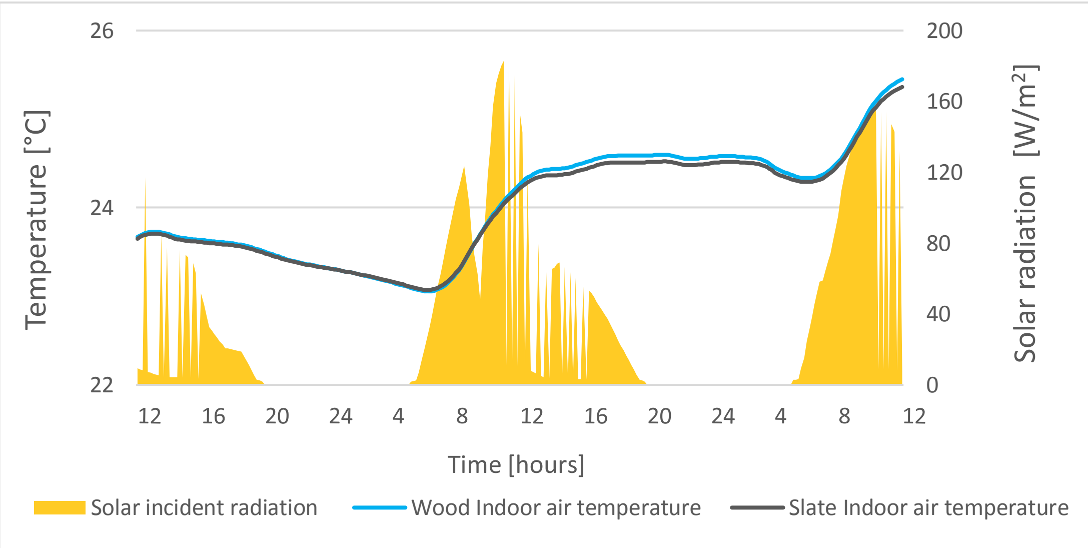

Figure 32.Solar incident radiation and indoor air temperature for a period of 48 hours, including the hottest day of the year: Model D with Wood and Slate

During summer, the influence of the different materials is less felt on the interior air temperature, because the shading device (blind) is used during most of the days. Besides the low influence on the indoor temperature, the solar incident radiation is intermittent which means that at a certain moment it reaches its peak and in the next moment it decreases to almost zero. This is all explained by the blind which is scheduled to close when indoor temperatures are higher than 23°C.

The presence of the blind during this day does not allow to show how the high thermal materials can have a positive effect on the air temperature. In this graph (Figure 32), when wood or slate are used the indoor temperature has the same behaviour, showing that the biggest benefit of using these materials in the windowsill and jambs is seen during the winter period because of their role as solar collectors.

There are only 4 days in the summer period when the shading device is not on and since the indoor temperatures are always so similar during the entire day, the differences that the materials cause are difficult to find.

4.2.6 The impact of the sun in the different materials

This section exhibits the comparison between the models when the materials are integrated in the windowsill and jambs and when they are not. Instead they are located in the west and east wall, roof and the floor, where they get no direct solar radiation. The amount of material used in these surfaces corresponds to the same amount that was applied to the windowsill and jambs' area. In order to compare the two types of window, models A, B and X were simulated. Model A is compared to model X and these simulations are done for the 2nd of February

4.2.6.1 Wood and slate with and without direct solar radiation

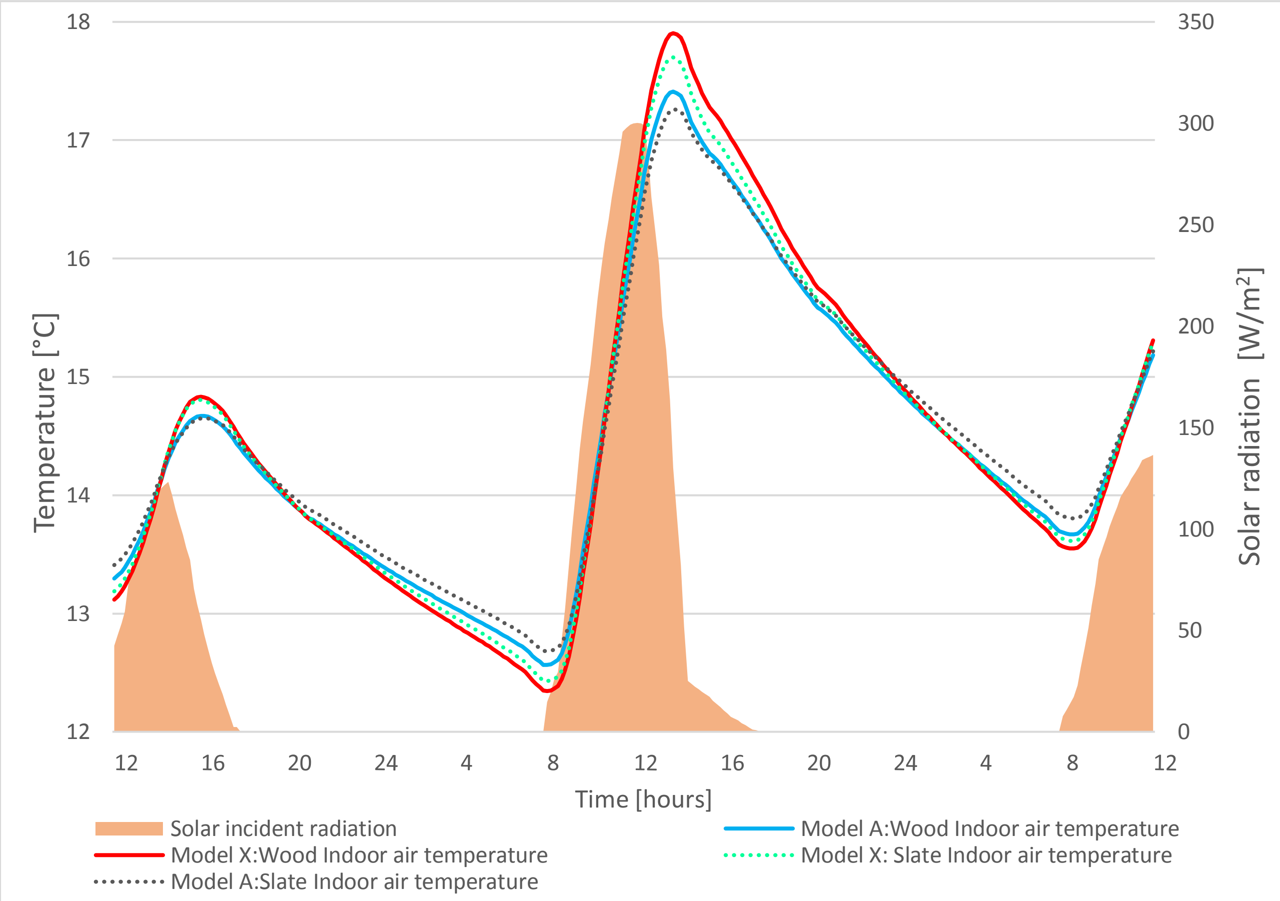

Figure 33. Solar incident radiation for the two window types and indoor air temperature during a period of 48 hours: Model X and A with Wood and Slate.

Model A and model X have the same window's area and for that reason the solar incident radiation is equal for both. The materials compared in Figure 33 are wood and slate in two distinct situations. In the model where the materials are not applied to the windowsills and jambs, the indoor air temperature reaches higher values. Conversely, in the case where the materials are applied on the windowsill and jambs, the inside temperature is greater when the minimum values are reached. This behaviour can be explained by the way solar radiation is split between the windowsill and jamb surfaces or dispersed within the space. When the windowsill and jambs are constituted by higher optical absorptance materials, a higher share of the impinging solar radiation is converted into heat within the material, thus not being immediately dispersed into the indoor air as heat. Hence the lower maximum air temperatures. Yet, when temperatures start to lower, that larger amount of absorbed solar radiation is released into the air from the higher thermal inertia materials, meaning that the indoor air temperatures do not reduce as much. While the impact is not very large, generally being smaller than 1°C decrease in the thermal amplitude, this solution still shows how the positioning of the material in a location with direct solar radiation can act as a delayed absorber of solar radiation, helping simultaneously to avoid overheating of the space and uncomfortably low temperatures over the daily cycle.

4.2.7 Comfort analysis

The comfort analysis was only done for the winter period since the summer period is affected by the shading device that allows for the indoor space to stay under comfortable conditions almost at all times. The indoor air temperature for the four models was compared to the maximum and minimum comfortable temperatures determined with the equations for the 90% acceptable limit written in chapter 2. The discomfort degree-hour was also determined in this analysis.

4.2.7.1 Winter period: Model A

Materials	Uncomfortable hours	Uncomfortable days	Discomfort degree-hour (°C.h)
Wood	1668	69.5	5130
Cork	1693	70.5	5049
Plasterboard	1669	69.5	5131
Granite	1662	69.3	4845
Brick	1640	68.3	4792
Slate	1613	67.2	4846
Marble	1675	69.7	4804

Table 7. Number of hours and days in which people will probably feel uncomfortable inside the building in the winter period: Model A

In this model, the materials that allow a comfortable space for a larger number hours are brick and slate. Cork is the material which makes the building more unpleasant, because it is normally used as insulation and for this reason is considered one of the materials with lower thermal inertia. The difference in the discomfort degree-hour coefficient between the low inertia materials, such as wood, cork and plasterboard and the high inertia materials is almost 200°C.h, which would translate to a significantly higher energy demand for the heating of the space.

4.2.7.2 Winter period: Model B

Materials	Uncomfortable hours	Uncomfortable days	Discomfort degree-hour (°C.h)
Wood	1684	70.2	6479
Cork	1694	70.6	6448
Plasterboard	1684	70.2	6471
Granite	1638	68.2	5998
Brick	1600	66.7	5742
Slate	1641	68.4	6272
Marble	1636	68.2	5903

Table 8. Number of hours and days in which people will probably feel uncomfortable inside the building in the winter period: Model B

All three low inertia materials have approximately 70 uncomfortable days inside the building. Brick allows 4 more comfortable days than the low inertia materials, which corresponds to 84 to 94 hours. The discomfort degree-hour coefficient in model B follows the same tendency as model A. Although there are some differences between the effects of all the materials in the indoor space, the percentage of uncomfortable days during the winter period is always below 55%. This value shows that more than half of the time during the winter period, people would probably feel uncomfortable inside the building. This must, however, be seen under the idea that no other internal gains are accounted for in these models.

4.2.7.3 Winter period: Model C

Materials	Uncomfortable hours	Uncomfortable days	Discomfort degree-hour (°C.h)
Wood	1948	81.1.	6141
Cork	1962	81.8	6219
Plasterboard	1947	81.2	6140
Granite	1949	81.2	5922
Brick	1937	80.7	6044
Slate	1937	80.7	6004
Marble	1966	81.9	6083

Table 9. Number of hours and days in which people will probably feel uncomfortable inside the building in the winter period: Model C

As predicted, model C has a larger number of uncomfortable days when compared to the other two models, A and B. This is due to the fact that in this model the building is facing southwest which does not permit the same amount of radiation to enter it, consequently resulting in almost 10 more uncomfortable days.

The materials that allow a more comfortable room are slate and brick, which in this case have the same number of comfortable hours. The minor difference between these two materials is the 40°C.h in the discomfort degree-hours coefficient. This difference can be explained by the fact that the indoor air temperature when slate is used does not have as lower values as when brick is used on the windowsill and jambs.

4.2.7.4 Winter period: Model D

Materials	Uncomfortable hours	Uncomfortable days	Discomfort degree-hour (°C.h)
Wood	1850	77.1	6632
Cork	1864	77.6	6731
Plasterboard	1849	77.03	6625
Granite	1826	76.1	6324
Brick	1807	75.3	6101
Slate	1803	75.1	6256
Marble	1828	76.2	6311

Table 10. Number of hours and days in which people would probably feel uncomfortable inside the building in the winter period: Model D

Model D enables more comfortable days than model C, because the amount of radiation that enters the building is higher since the window area is larger.

When compared to model B, this model has approximately 8 more days when people feel uncomfortable indoors. The fact that in this model there are more uncomfortable days is explained by the orientation of the building. Since the building is facing southwest the radiation that reaches the building is much less than when it is facing south. Less radiation means lower indoor temperatures, which makes this type of building more uncomfortable.

In model D, the discomfort degree-hour coefficient is higher for the low inertia materials, which shows that when these materials are on the windowsill and jambs the indoor temperature is both further from the minimum comfortable temperature range and for a larger period of hours.

4.2.8 Average thermal amplitude

The thermal amplitude between the maximum indoor air temperature and the minimum air temperature was also analysed. Table 11 confirms that the high inertia materials period such as granite, brick, slate and marble in winter significantly reduce the average thermal amplitude in the building. This fact explains the overall performance of high thermal inertia materials since the indoor temperatures reached inside the building have less fluctuation. In general, there is a clear demarcation between the low and high thermal inertia materials, which is reflected by approximately 0.5°C average difference over the winter period.

In the summer period, while the effect is still observed, the thermal amplitude has more similar values for all of the models (with an average difference of just 0.1°C), because the shading device is activated on almost all days.

Given the small areas that the windowsill and jambs have when compared to the space's volume, it is interesting to see that their effect is still clearly noticeable and at a range that would probably have a significant impact both on comfort and on energy demand for heating.

Models/Materials	Model A Winter	Model A Summer	Model B Winter	Model B Summer	Model C Winter	Model C Summer	Model D Winter	Model D Summer
Wood	4.3	1.4	6.4	2.0	3.7	1.5	5.5	2.0
Cork	4.2	1.4	6.4	2.0	3.6	1.5	5.6	2.0
Plasterboard	4.3	1.4	6.4	2.0	3.7	1.4	5.5	2.0
Granite	3.9	1.3	5.7	1.9	3.3	1.4	4.9	1.9
Brick	3.7	1.3	5.4	1.8	3.2	1.3	4.7	1.8
Slate	4.1	1.3	5.9	1.8	3.5	1.4	5.0	1.9

Marble	3.8	1.3	5.7	1.8	3.3	1.4	4.9	1.9

Table 11. Values of average daily thermal amplitude for all the materials during the winter and summer periods.

5 Discussion of the results

The obtained results for the summer and winter periods were reasonably distinctive, thus the following analysis must begin with the description of the differences between both periods.

During the considered summer period, the choice to using the automatic shading decreased the materials' influence, contrarily to what happened in the winter period, since the blind was only shut during the night, which therefore did not affect the entrance of solar radiation into the building.

The indoor temperature during the summer months was mostly higher than 23°C, and for this reason the blinds were shut all day long. Still, the shading device showed to be quite effective and maintained indoor conditions at comfortable levels throughout most of the period. The activation of shading kept excessive sunlight from entering the building, thus avoiding the risk of overheating. In the majority of days during the summer period, people feel more comfortable inside the rooms.

This is particularly relevant as the absence of shading would probably result in very poor performance when high inertia materials would be present in the windowsill and jambs. It would be expected that these would potentiate an even higher overheating of the space by favouring even more effective absorption of excessive solar radiation into the indoor space. By using shading, the benefits of the high inertia materials in the winter period are possible without the corresponding negative impact in the summer.

The assessment of the materials is therefore constrained by the shading during summer. Thus the results of the spaces' indoor temperatures are quite similar, and are mostly influenced by the shading performance, not by the studied materials. The fact that the surfaces built with high thermal inertia materials do not heat up as much as the low thermal inertia materials is one of the main differences observed. (4.2.4) This allows for the interior temperatures of the building to be slightly milder.

The charts presented in the "Results" chapter concern the influence of the materials on the spaces' interior temperatures, the windowsill and jambs' temperatures, as well as the absorbed radiation by these surfaces during the winter period.

One of the first differences exhibited in the charts is the behaviour of the materials throughout the day. When low thermal inertia materials are present in the construction, the interior temperature has a higher thermal amplitude, which means that during the coldest and hottest hours, the temperature in the interior space is lower or higher respectively.

The presence of high thermal inertia materials in the building allows for these temperature ranges to be attenuated, that is to say the temperature throughout the day does not hit extremes as severe as when using low thermal inertia materials.

When there is less fluctuation regarding exterior temperature, or in other words, when the temperature values are constant throughout the days, the effects of the thermal inertia of the materials are less felt than on days on which the differences in exterior temperatures are higher, most probably because this effect is accompanied by a corresponding lower amount of direct solar radiation impinging on the surfaces.

The absorbed radiation is greater in the case of materials with higher absorptance properties, which causes the temperatures of the windowsill and jambs which contain these materials to be higher. One of them is slate, which apart from being the studied material with the best optical properties, it is also among the ones with the best thermal properties.

The different areas of the tested windows showed that an extra 0.5 m^2 of area could lead to the increase of up to approximately 2.5°C (4.2.2) in the indoor temperature, for a room of 16 m^2. This significant rise is a direct result of the larger amount of radiation coming through the glazing but is also further potentiated when massive materials are used in direct exposure to the sun, namely in the windowsill and jambs.

The impact of the windows' orientation, here tested as an alternative scenario rotated by -45° off south (i.e. oriented towards southwest), revealed similar trends of the indoor temperature as the ones seen when the window faces south. Nevertheless, the registered interior temperatures are not as high as in the case of the south-facing window, since the quantity of radiation transmitted indoors by the window is lower. The difference in temperature between when the building is facing south or when it is facing southwest can be up to 3°C.

The indoor temperature in the window oriented towards southwest has a roughly equal behaviour to the one shown when wood and plasterboard are used in the construction. The temperature does not reach as high figures in the case of slate or brick, yet the minimum temperatures are higher than when wood, cork or plasterboard are used.

In the models where the tested materials are placed away from direct solar radiation, the indoor temperature tends to reach peaks that are higher at the maximums and lower at the minimums when compared to the scenarios with the materials in direct sun light. This observation is justified by a higher radiation absorption when it falls directly in the darker and higher inertia materials, which convert it into heat, thus refraining the indoor air temperature rise, but then release that heat during the times when indoor temperature decreases, thus avoiding such low temperatures. This effect shows the clear additional benefit, over just the thermal inertia increase, of using the massive materials in the windowsills and jambs.

The comfort analysis conducted in the winter period, made it possible to check that during the months of the winter period, from January to April, people felt uncomfortable inside the building in more than half of the time. This means that the indoor temperature of the space was not within the temperature range of the thermal comfort defined using the adaptive comfort ASHRAE norm. In the majority of days of this period, the interior air temperature is inferior to the minimum temperature of comfort. This issue would, however, be lower if considering the always present internal gains that a regular space would have, such as people, lights and other devices. For the purposes of this work, thus, the comfort analysis is more relevant from a comparative perspective than from an absolute one. And in this case, the difference is clear, in as much as the high inertia materials, even when applied in the small areas of the windowsills and jambs, still have a small but clear beneficial impact on the indoor thermal environment.

6 Conclusions

In the aftermath of the work developed throughout this dissertation it is possible to draw relevant conclusions, namely within the framework of thermal inertia and the influence it has on the interior space when it is placed on the windowsill and jambs.

The first conclusions to be drawn were the impact the placement of high thermal inertia materials in windowsill and jambs had on the building, not only regarding temperatures which were reached in the interior, but primarily their influence on the interior thermal comfort. The impact is not very large, especially in what comes to the indoor temperature which is achieved when placing those materials in the windowsill and jambs, but this must be seen under the perspective that the areas of intervention were relatively small when compared to the size of the room. Nonetheless, some differences within interior temperatures are still noted, in particular the absence of severe extremes, that is, the inexistence of remote temperature maximums and minimums. Low thermal inertia materials possess a rather distinct behaviour: they heat up and cool down more quickly, which renders the temperature of the space not as constant throughout the day.

While thermal comfort conditions are only reached on less than 50% of the time during the winter period, the results still clearly showed that the higher mass materials in the windowsill and jambs, achieved comfort conditions more frequently or were closer to offering it. It is not clear if a higher amount of material, either through a use of a thicker constructive element (which was just 2 cm in this work), or through a larger area, would result in a proportional improvement of the comfort conditions.

One of the potential issues with the placement of highly absorbing materials in direct solar radiation, could be the worsening of comfort conditions during the summer period. However, the adequate use of automatic shading devices in this work showed that comfort conditions could be maintained almost all of the time.

Out of the windowsill and the two jambs, the surface that showed the greatest thermal potential depended on the orientation of the window, as well as the height of the sun. If the window is facing south, the windowsill is the surface which can absorb the highest quantity of radiation and for this reason it is the one that gets warmer. Thus, it becomes the greatest contributor to the rise in indoor temperature, particularly in the winter period. If, alternatively the window is facing southwest, then the windowsill is no longer the surface with the highest thermal potential but, instead, it is the east jamb.

Out of the high thermal inertia materials tested, the one showing the biggest impact in the indoor environment was slate. Slate is the material which possesses the best optical properties, or in other words, the greatest solar and visible absorptance values. This means that this material has a higher capacity of solar radiation capture, and, as a consequence, the surfaces that contain them heat up more than the ones that do not possess slate in their composition. Additionally, this material also has high specific mass and specific heat, making it a high thermal inertia material. Its optical and thermal properties provide a higher indoor temperature in winter when compared to the other high thermal inertia materials. The minimum temperatures of a given space when slate is used will never be as low as when low thermal inertia materials are utilised.

The results showed that the use of massive materials, particularly ones with high optical absorptance, in the windowsill and jambs of windows facing south, can be an interesting technical option to compensate for the lack of internal mass in buildings where walls have to be insulated internally. Despite representing just a fairly small area, their position in direct exposure to sun radiation significantly potentiates their impact on thermal inertia. This ultimately results in lower heat demand for the space and, consequently, a lower environmental impact, while exploring a very simple and fairly cheap way of implementation.

7 Future projects

Phase changing materials are one of the topics which were not analysed in this project, but still documented in the state of art. Nowadays, these are the most studied materials in what comes to thermal inertia, since they offer rather satisfactory results with a wider flexibility of applying them in more diverse circumstances and materials. Due to the strict deadline for the completion of this dissertation, the focus was instead put on the most commonly building materials used in the construction industry. Still, as a future project, a study regarding phase changing materials and their potential impact when used in windowsill and jambs would be a feasible option.

The simulations were run for a space with generally low thermal inertia, with plasterboard and insulation covering the internal walls. However, it might also be interesting to confirm if the impact of the solutions here tested would still be observable in spaces with higher thermal inertia.

A detailed analysis with different variables such as the adding of internal gains and different dimensions for the interior space would also be interesting in order to test a space more similar to a real building.

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